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ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

R.A.R.D.E. MEMORANDUM 34/70

GUNS AND AMMUNITION DIVISION

Gun Blast and Muzzle Brake Symposium (U)
R.A.R.D.E. Fort Halstead 5th - 7th March 1968
(title UNCLASSIFIED)

Fort Halstead
Kent.

November, 1970

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ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

R.A.R.D.E. MEMORANDUM 34/70

Gun Blast and Muzzle Brake Symposium
R.A.R.D.E. Fort Halstead 5th - 7th March 1968

(title UNCLASSIFIED)

G.R. Nice, B.Sc. (E4 - formerly B2)

Summary

A full account is given of the Symposium which covered Experimental Techniques for measurement of blast and muzzle brake performance, Research, Development and Design of muzzle brakes and Physiological Aspects of Gun Blast.

Approved for issue:

F.H. Seeley, Principal Superintendent, 'B' Division

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FOREWORD

There has been a very considerable, and most unfortunate, delay in preparing this report for publication.

This has been due to the pressure of other work and also to difficulties in obtaining texts and illustrations from certain contributors, even now a few illustrations which it was hoped might be included are not available.

Apologies are offered for the delay and it is hoped that it will not detract too greatly from the value of this report.

November 1970 G R NICE

PART 1. OUTLINE OF SYMPOSIUM

1. INTRODUCTION

A symposium on various aspects of gun blast and muzzle brakes was held at the Royal Armament Research and Development Establishment on 5th - 7th March, 1968 and it was attended by over 60 representatives from 5 countries (see Annex A).

The proposal for the symposium originated during F.R.G./U.K. discussions on gun blast and muzzle brakes during initial stages of collaboration between the two countries on the development of a 155 mm towed gun - the FH 70 Project - but it was felt that it would be useful to have discussions dealing with the broader aspects of the subject rather than to confine them to a specific weapon.

Arrangements for the meeting were made very largely by D.G. of Arty (Major D.R.H. Longfield) and it was chaired by Mr. F.H. Seeley, Principal Superintendent, B Division, R.A.R.D.E. The arrangements included provision for simultaneous English/German translation and this contributed quite largely to the success of the meeting.

Following introductory remarks the symposium was divided broadly into three sessions:-

I	Measurement:	the basis of all research and development, covering both blast and muzzle brake efficiency,
II	Development:	the use and application of these measurements to achieve practical results in the reduction of recoil energy with the minimum adverse changes in blast pattern,
III	Physiological Aspects:	covering the effects on gun crews and others in the vicinity of blast due to gun fire.

The programme followed is given at Annex B.

Because of a lack of foreknowledge of the precise content of each presentation to be given there was, unavoidably, some overlap of subjects between sessions.

The remainder of this Record gives a summary of each session followed by details of presentations made with, where appropriate, an account of ensuing discussion. In most cases details of the presentations are as supplied by the person who gave it and there is a considerable variation in amount of detail given though an attempt has been made to secure some degree of uniformity by editing.

In the few cases where written presentations were not available details given have been compiled from notes made during the meeting.

2. MEASUREMENT AND RESEARCH

This session covered some of the basic techniques used in the study of gun blast and muzzle brakes.

After a brief introduction on techniques of measurement details were given of two basic types of device used for measuring gun blast pressures; simple foil rupture gauges used for a quick assessment of maximum pressure at a point and more sophisticated piezo-electric transducers used to obtain an accurate pressure-time history of a blast wave. Some details were also given of the measurement of noise.

These presentations were followed by an account of the system used by F.R.G. at the Meppen Proving Ground for measuring recoil and then by a description of very extensive studies of muzzle brakes and muzzle blast carried out on a model scale.

The session ended with a presentation of full calibre studies, linked with this model work, and this included an account of the methods used by U.K. for measuring recoil and the efficiency of recoil-reducing muzzle fitments and their effects on blast patterns around a gun.

3. DEVELOPMENT

This session was concerned with the problems associated with the practical development and design of muzzle brakes for specific weapons. The first presentation gave an historical survey of the problem as seen by U.K. and this was followed by F.R.G. and U.S. speakers who emphasised the especial problems of obtaining a reasonably high muzzle brake efficiency without raising blast levels at gun crew positions to objectionably high values.

Specific results were quoted in some detail for 155 mm and 105 mm calibre firings.

The final presentation was a description of studies made in U.S. at the Ballistic Research Laboratories of the effect of muzzle gas dynamics on a small arms weapon and its firer, regarding man and weapon as a single system.

4. PHYSIOLOGICAL ASPECTS

This session was concerned with the effects on human beings in the vicinity of noise and blast from guns and contained presentations by U.K. and U.S. on the different effects on hearing produced by such phenomena. The session included a film produced by the Royal Naval Medical School on "Dangerous Noise".

5. CONCLUDING REMARKS

In a final discussion period it was generally agreed that the symposium had been of considerable value as an exchange of information on the various aspects of its subject. It was felt to have been of particular value in bringing together those working on these different aspects of the countries represented who do not normally come into contact with each other; for example actual designers of muzzle brakes and those interested in the physiological aspects of gun blast.

It was felt that it would be of interest to consider another similar meeting in a few years time.

PART 2. DETAILS OF PRESENTATION

SESSION I - MEASUREMENTS AND RESEARCH

Item 1 Introduction to Measurement G.R. Nice, B2/R.A.R.D.E.

As in many other fields of scientific and technical endeavour accurate measurement of the parameters involved is essential to any studies of gun blast and muzzle brake effects.

As far as U.K. work in this area is concerned we have used a number of quite distinct techniques. I propose merely to introduce these techniques leaving it to subsequent speakers to elaborate on them.

For many purposes an indication of the peak blast pressure distribution around a gun is all that is required; this is very easily and simply obtained with a foil rupture gauge. In this a thin standard foil is held so that different areas are exposed by holes of differing diameter so that the foil will be ruptured by impinging blast; the size of the hole ruptured gives a measure of the blast level.

Such gauges are simple and cheap and may be deployed in large numbers. As the next speaker, Mr. Bicker, will tell you they may be refined to cover a wide range of pressures and to give quite a sensitive and sophisticated measuring device. (Item 1.1).

For more accurate measurements especially where effects on structures or equipment are concerned a pressure-time history for the blast is required and this is obtained with a piezo-electric gauge which the speaker under item 1.2 (Mr. Green) will discuss.

We have also found a "flow visualization" technique to be very useful in some cases. In this blast is photographed against a black and white striped background with a high speed camera and the density discontinuity at the shock-wave becomes apparent.

The final type of measurement to be employed are noise measurements which Dr. Elwood will consider under item 1.3.

Item 1.1 Foil-Rupture Blast Pressure Gauges A.W. Bicker, F1/R.A.R.D.E. Potton Island

Introduction

The accepted method of measuring blast pressures around gun muzzles or from high explosives is by name of piezo-electric transducers and electronic recording equipment, and this will be discussed later under item 1.2.

However, the equipment involved is bulky, relatively complex, and requires trained personnel to operate and assess the results.

In addition circumstances often arise where such equipment is either not available or not available in sufficient quantity to make all the measurements required as in determining the pressure contours round a gun at various heights and distances or it could be that trial conditions would be hazardous to personnel and equipment.

So far as is known foil gauges of the type under discussion were first developed by F.V.R.D.E. for a specific requirement but they have undergone considerable modification in R.A.R.D.E.

Although they have limitations, foil gauges are very useful in circumstances, to augment the more sophisticated system or where the general picture is required rather than detailed information at a few points as would be provided by the piezo-electric system. The limitations of foil gauges are (1) their accuracy, which at present is only slightly better than ± 10% and (2) the fact that they only show peak pressures, although this may not be too serious if the general shape of the pressure wave is known by experience or from other measurements.

Foil gauges are simple, robust, can be exposed in large numbers, and can be used by unskilled operators.

Essentially they consist of a thin metal diaphragm or foil, usually aluminium, clamped over apertures of various diameters, and when exposed to blast the foils rupture at a surprisingly reproducible pressure level. The rupture pressure depending, of course, on the aperture diameter and the thickness of the foil.

The foils are weak and inertialess, and fail by pressure and not by impulse (pressure-time integral). To confirm this, foil gauges have been calibrated by exposing them to blast from explosive charges and monitoring the pressures by the piezo-electric system. The gauges were exposed at the same pressure level to blast from a range of weights of explosive charge and thus the only variation is in the duration of the pressure wave. Charge weights used ranged from 1 to 64 lbs giving a 1:4 ratio in duration and it was found that all foils behaved similarly. This was further confirmed on a firing of 4000 lbs HE which gives a duration ratio of 1:16, and the foils failed at the same pressure level as from the smaller charges.

Calibration

Foil Gauges can have a number of apertures of very different diameters and so cover a wide range of pressure, or they can be used to cover a narrower range with greater resolution.

A type of gauge which has just been calibrated is shown in Figs. 1 and 2. This has four sizes of aperture - 1.4, 0.8, 0.32 and 0.16 inches diameter, and covers pressures from 1.5 to 40 psi. A top plate clamps the foil flat over the apertures in the body, and there is a backing plate to prevent blast gaining access to the rear of the foil after diffracting round the body. The entry to the holes in the top clamping plate are chamfered to try to cover circumstances where the blast is not truly normal to the gauge, and also to avoid diffraction which would occur round sharp-edged holes. As will be seen later this chamfer caused some trouble.

The foil used was annealed commercially-pure Aluminium, .008 mm thick, which had been purchased in bulk and was therefore of the same thickness and in the same metallurgical condition. Multiple foils were used to obtain diaphragms of varying thickness to cover a wider range of pressures.

The blast pressures were not monitored in this trial, because as a result of hundreds of firings in which pressures from explosives have been measured, the pressure/distance relationship, is known with an accuracy of $\pm$ 3-4%, and this data was used to determine the pressure at which the foils ruptured. At present it is still necessary to calibrate each design of gauge and the object of this trial was to see if some relationship could be resolved which might eliminate this work.

The foil gauges were exposed in groups of three at slightly different radial distances facing the charge, figs. 3 and 4, and the positions of the groups adjusted so that the pressure to cause rupture was bracketted. At the critical pressure level for each diameter of aperture the front foil of a group ruptured, the rear foil failed to rupture, and the centre foil was in the 'go/no go' region.

As stated previously the foils rupture at a very reproducible pressure level and also in a very reproducible manner, the criterion for rupture is a pinhole sized perforation right in the centre. This particular type of perforation may be due to the fact that when a clamped diaphragm is deformed by shock loading it does not move into a rounded form, but deflects as a truncated cone, with bending waves moving in from the periphery and meeting at the centre to produce the perforation.

There are obviously various degrees of rupture, from the complete shearing round the periphery, tearing across, the pinhole puncture, and buckling without rupture fig. 5. After exposure the foils always appear buckled to some extent (presumably due to turbulence and interaction of pressure waves).

The fact that at the critical pressure the pinhole rupture is in the centre, is very useful in that small punctures other than in the centre can often be ignored as being due to dust or small particles of debris.

Results

The critical rupture pressure was determined for each size of aperture with diaphragms of various thickness. The results are shown in log/log graphs, (figs. 6-9), which show D/t against free field pressure; D being aperture diameter and t diaphragm thickness, the diaphragm being made up of various sheets of standard .008 mm foil. Before discussing the results it should be made clear that the rupture pressure quoted is the free-field, side-on, or hydrostatic pressure (P_i) existing in the pressure wave without any obstruction, whereas the foil ruptures as a result of the reflected or face-on pressure (P_r). In ideal circumstances P_i and P_r are related by

$$P_r = 2\,P_i \left(\frac{7P_o + 4P_i}{7P_o + P_i} \right)$$

but this relates to an infinite rigid surface. (See fig. 10).

Side-on calibration pressures are quoted for two reasons. When a blast wave impacts the surface of a target, rarefaction waves are generated at the target edge and move inwards across the target face and erode the positive pressure wave. While this is not very significant here since the foils fail instantly under the peak pressure, someone may push the design to the limit so that the foil comes right to the edge. The other reason is the condition in the theoretical relationship that the target is rigid, and of course this is something which can vary according to the trial requirements.

Reverting to the results, the fit of the lines shows there is a relationship between $\frac{D}{t}$ and P_i and this is of the form

$$\log \frac{D}{t} = -\,m \log P_i + C \quad \text{(C is a constant)}$$

$$\text{i.e. } \frac{D}{t} = P_i^{-m} \times C'$$

$$\frac{\frac{D}{t}}{P_i^{m}} = \text{constant}$$

and from these curves $m \doteqdot 1.3$

The tests were made only over a limited pressure range of P_i from 1.6 to 40 psi which it was thought would be of interest in respect of damage to personnel or equipment.

The pressures at which the foils rupture is reproducible between about $\pm$ 5% as can be seen from the table, fig. 11, this together with the estimated accuracy of the pressure/distance data used in calibrating, suggests that foil gauges will measure the peak pressure with an accuracy slightly better than 10%.

Discussion

Each of the calibration graphs looked reasonably good, but when all the results are plotted together as in fig. 12 there is some disparity. This is attributed to the funnelling effect of the chamfer on the entry holes in the top plate. This disparity is greatest with the small apertures, and for this reason it is suggested that it is preferable to use the larger apertures with thicker diaphragms to give the required $\frac{D}{t}$ ratio for the pressure to be measured.

To investigate this further gauges of a modified design with a 1/8 inch thick top plate will be calibrated, to see if the graphs can be made more coincident. Obviously it would be desirable to devise an arrangement when the foil is flush with the surface. This would permit design of side-on gauges on the rupture-foil principle.

The effect of shape of entry hole was investigated using a special gauge with a single 0.25 inch diameter aperture and differing entry shapes (fig. 13). This modification increased the rupture pressure by 3% and brought the results more in line with those from the larger apertures.

To obtain foil of known and constant thickness, and in known metallurgical condition, it has to be ordered in large quantities. To assist the occasional user, the gauges were calibrated using various commercial cooking foils. The results were not very good, different makes varied between .016 and .019 mm in thickness, there was variation in thickness within a given sample, and the material is in an unknown half-hard or hard condition from the rolling process. Annealing the commercial foils did not greatly improve the results. The results are shown in figs. 14-16.

Conclusion

In conclusion although foil gauges only indicate peak pressure and in the present state of development are only accurate to approximately $\pm$ 10% there are many requirements for which they can be very useful.

Within R.A.R.D.E. they have been used to determine pressure contours in muzzle blast, to measure the order of detonation from bombs by establishing a pressure/distance relationship and to estimate the pressures in a rocket efflux.

From the enquiries we have received it appears that further work might be justified to improve the design and extend the pressure range at both ends.

At the low pressure end it would be interesting to see the effect of the rise time of the pressure. It is possible that the system would work on other than a steep-fronted shock wave providing the rise time is short compared with the natural frequency of the foil diaphragm. In which case it might be possible to extend the pressure range down to 0.5 psi or less, where the shock wave begins to decay into a rounded sound wave.

At the other end of the scale it may be that a limit will be reached where the stiffer and stronger diaphragm will be impulse-sensitive, instead of pressure-sensitive, and then if two variables - Pressure and Time - are involved, the system will lose its attractiveness.

Item 1.2 Piezo-electric measurement of gun blast pressures K.E.B. Green, B2/R.A.R.D.E.

The 'piezo-electric' effect has been known since very early eighteenth century; however the first serious study is attributed to the brothers Curie, Piere and Jacques, in 1880, who observed and measured the electrical charges produced when certain crystals are subjected to pressure.

Piezo-electricity is defined as the electrical polarization produced by mechanical strain in crystals belonging to certain classes, the polarization being proportional to the strain and changing sign with it. It is a reversible effect, and is exhibited by many natural crystals, notably tourmaline, quartz, topaz, Rochelle salt, sodium chlorate and tartaric acid. The mechanical strain may be produced either by a hydrostatic pressure around the crystal or a unidirectional stress along a particular axis. Some crystals respond greatest to tri-axial stress (e.g. tourmaline) and others to uniaxial stress (e.g. quartz).

For gun chamber pressure recording a tourmaline crystal is used and is subjected to the gas pressure via the medium of a grease and/or plasticine material. Its sensitivity and pressure levels are such that a single crystal can give a sufficiently large output and be housed in a convenient size gauge body.

For blast pressure measurement a gauge of approximately 1,000 times the sensitivity is required and use of tourmaline is impracticable. The greater sensitivity of quartz when X-cut crystals are loaded axially is used and even then the output of several crystals must be aggregated.

Each crystal is .02 inch (.5 mm) thick and just under 1 inch (25 mm) dia. They are made into a stack of 12 gauges with positive-going surfaces alternately up and down and are interleaved with thin copper foil electrodes .003 inch (.075 mm) thick. These are all stuck together with a low melting point wax with a .1 inch (2.5 mm) duralumin pressure plate on either side to act as a piston. The whole stack is sealed with a pair of neoprene diaphragms into a steel body cell (fig. 1).

The cell is itself inserted into a streamlined baffle which allows the blast wave to pass over the sensitive measuring surfaces without undue disturbance or attenuation of the blast wave. This is a bi-directional gauge and is used vertically, pointed towards the blast source such that both direct and ground reflected waves see the gauge body edge on. The gauge itself is attached to an insulated handle which preserves the streamline effect and is then mounted on a lightweight collapsible stand (fig. 2). This can support the gauge at any height up to about $6\frac{1}{2}$ ft (2.0 m).

For a complete survey around a gun barrel up to six gauges are used at varying distances along either one or two selected azimuths (from muzzle and line of fire) depending on the number of channels available in the recorder.

After two or three successful rounds with this set-up, the line of gauges will be moved to another azimuth; these are usually selected at 15° intervals.

The peak pressures are measured off the oscillograms, plotted for each azimuth against distance and certain pressures interpolated to enable isobars to be plotted on a plan around the gun barrel.

The analysis is complicated by the fact that in general the gun barrel and the gauges are not at ground level and the gauge may respond separately to the direct blast wave and its ground reflection arriving a few milliseconds later. However, at the gauge position there will be a Mach stem wave (the direct and reflected wave combined) extending from the ground. The height of this Mach stem increases with distance from the gun.

In the R.A.R.D.E. it is usual to add the direct and reflected peak pressures and to regard these sums as a measure of the Mach stem pressure existing at the gauge position to enable Mach stem isobars to be plotted.

Figs. 3-5 give the layout of gauges for a particular trial in which gauges were used at fixed positions to record blast pressures, with and without muzzle brake.

Fig. 6 shows a typical blast oscillogram where individual gauge positions varied in height, distance and azimuth. Gauges forward of the gun, in particular channel 9, from the bottom, record the projectile bow wave followed later by the blast wave.

Discussion

The physical size of Piezo-electric blast gauges introduces an error into the peak pressure measured. If the radius of the transducer sensitive area is δ and the shock wave velocity is V then the recorded over-pressure p' may be expressed approximately as

$$p' = p\left(1 - \frac{\delta}{VT}\right)$$

where T is the positive phase duration; the shock wave-form is here assumed to be sharp pointed with linear decay.

Accurate plotting of blast contours around a gun is necessary since small movements of gun crew members can place them in a potentially dangerous position.

Item 1.3 The measurement of noise Dr. M.A. Elwood, A.P.R.E.

Noise has been defined as unwanted sound. It is experienced in two distinct forms in man-made environments, as Continuous Noise generated, for example, by vehicles and aircraft, and as Impulsive Noise - for example, that produced by a large drop hammer or by guns. Blast may be regarded as a sharp-rising impulsive noise, but not all impulsive noises are blast.

For many years blast has been measured by direction sensitive gauges, of a simple mechanical type, for example the rupturing foil gauges, or of the more sophisticated piezo-electric type. The orientation of these gauges must be taken into account before interpreting the transient peak pressure recorded.

The use of omnidirectional microphones has formed the standard technique for measuring continuous noise as the root mean square value of the sound pressure level. In parallel with the production of more intense noise from aircraft engines, there has been a development of more robust microphones which has permitted their use in the measurement of transient peak pressure levels up to a few psi. It is anticipated that the use of a one-eighth inch omnidirectional condenser microphone may permit reliable measurements up to about 10 psi. The precise orientation of such a small microphone may not be so important as with the relatively large blast gauges. If this is true then it may be preferable to use microphones rather than blast gauges to assess the pressure time patterns in confined or restricted spaces where pressure pulses are reflected from surrounding surfaces. Directional Piezo-electric blast gauges tend to produce a complex pressure-time history in these circumstances which is difficult to interpret, as any particular spike on the record may be an incident or a reflected pressure according to its orientation to the gauge, which may well be unknown. In the same way the orientation of a mixture of pressure pulses to an omnidirectional microphone may be unknown, but because of its relatively wide acceptance angle interpretation may be easier.

Often pressure measurements are required for the identification of evaluation of potential hazards. It is vitally important that the technique of measurement used in defining any criterion for human safety is the one selected for the evaluation. For lung injury or ear drum rupture, measurements have been made with direction sensitive blast gauges in the side-on mode. Microphones have been employed more often in relation to inner ear damage. .

The use of different units of measurement is an added complication. The dB is the unit preferred by those who study 'noise' and psi for those working on 'blast'. Conversion from one to the other is relatively easy with a nomogram (1 psi ≡ 170.8 dB, referred to 0.0002 dyne per sq cm, the limit of 'normal' audibility, as zero). As further examples 1 lb per sq ft ≡ 127 dB; 5 psi ≡ 180 dB. Conversion of measurements made by direction sensitive gauges in one orientation to those appropriate for another may not be possible.

With a $\frac{1}{4}$ inch crystal microphone there is a 2 to 5 dB difference between side and face-on measurements. The difference is less but still significant with an $\frac{1}{8}$ inch microphone. Similar effects are observed with the human ear; at auditory levels there is a 5 dB difference in effect between side and face-on noise.

In establishing criteria for damage, peak pressure must be linked with duration. Estimation of duration is simple with a simple impulsive noise where it can be defined as the time for pressure to return to its base level. With oscilliatory noise it is usual to define duration as the time for the envelope of the oscillations to fall by 20 dB from its peak level.

Item 2 Recoil Measuring Equipment at Meppen Herr Hornfeck, F.R.G.

In all work to determine the performance of muzzle brakes it is necessary to determine the impulses imparted to a gun barrel with and without such fitments.

The usual method of doing this is by measuring velocities of recoil under "free-recoil" conditions. Actual methods of measuring velocity will be described later (Session II item 2); this presentation is concerned with a free recoil mounting.

The original mounting in use at Meppen, built by Rheinmetall in 1958, could not handle all types of barrel and could not cope with maximum performance conditions. The mounting was subject to considerable vibration and was difficult to handle.

In designing a new free recoil mounting it was desired that these shortcomings (due mainly to the fact that the old mounting had to be constructed largely using items from other existing equipments) should be eliminated and that the mounting should cope with at least all barrels from 90 to 155 mm in calibre, larger if possible.

The new recoil measuring equipment is in four basic parts

1. The recoiling carriage,
2. the runway rail bed,
3. the buffer recoil system,
4. the actual barrel under test.

Some details of each part are given below.

1. Recoiling Carriage

This weighs about 5.5 tons and is made of unalloyed cast steel and runs on 4 track wheels with side pressure rollers to damp out possible vibration.

The effective length of the carriage is adjustable, since the front and rear members are connected by tie-bars whose length may be varied to suit the gun barrel under test.

The front member is in the form of a V-block so that the axis of the barrel in use may be adjusted to ensure that the centre of gravity of the loaded carriage lies on this axis.

The rear member is designed to take the shock of impact with the recoil system which it strikes after about 600 mm of free recoil.

Devices for measuring recoil velocity are mounted under the front part of the carriage.

2. The runway rail bed

The rail bed is also of cast construction and is secured to a secure foundation by anchor bolts.

The actual rails are fitted with hardened guide ribs.

3. Buffer recoil system

This consists of a hydraulic buffer and a hydro pneumatic recuperator which are both mounted in an anchor plate secured to the equipment foundation.

The most important elements of the buffer are an hydraulic cylinder, a piston rod with the buffer piston and a regulating bush.

When the carriage strikes the head of the piston rod, which is fitted with a rubber pad to absorb some of the impact, the piston is forced into the hydraulic cylinder and this pushes the oil with which it is filled out through regulating grooves. In this process the kinetic energy of the recoiling carriage is converted into heat. Expansion of the oil due to this heating is compensated by the motion of the piston rod in the initial position of the recoil system. This ensures that there is no initial pressure in the system since the increase in volume of the oil is balanced by the increase in effective cylinder volume due to the piston rod motion out of the cylinder.

The hydro pneumatic recuperator consists of a storage cylinder with an internal recoil recuperator cylinder and a recuperator piston and rod. This piston rod is connected to the buffer piston rod by a cross bar. The storage cylinder is filled with oil so that its level is above the recuperator cylinder with the space above the fluid filled with nitrogen initially at 20 atmospheres pressure. Motion of the buffer piston on recoil compresses the nitrogen further and when recoil is complete the expansion of this gas restores the equipment to its initial state.

A disc valve in front of the recuperator cylinder regulates the run out velocity.

4. The Test barrel

This is mounted between the front and rear parts of the recoiling carriage by means of the tie-bars; correct mounting being essential to ensure valid results.

It is expected that this new recoil measuring equipment will come into use at Meppen early in 1969 and that it will be of great value in the future testing of muzzle brakes on a variety of weapons especially the 155 mm FH 70.

Measurement techniques used with this equipment are described in a later presentation.

Item 3 Muzzle Brake Model Studies F. Smith, D4/R.A.R.D.E.

Introduction

The problem of alleviating the recoil of guns is one that has been in existence since the earliest development of the gun. One of the first attempts to use the combustion gases to reduce recoil was about a century ago by the Frenchman, Col. Chevalier Treville de Beaulieu who drilled rearward facing holes in a rifle. Since then there have been a large number of full-scale trials of muzzle brakes but it is difficult to obtain from them logical parametric variations. This problem seems to provide an ideal opportunity to make use of model experiments but as far as the author is aware the only such tests were made by Oswatitsch (ref. 1) in 1943, using 2-dimensional models in a free jet sonic wind tunnel. It was therefore decided to conduct a comprehensive series of 3-D model experiments at R.A.R.D.E. using steady flow techniques and with air as the working fluid (theory predicts, and some preliminary experiments showed, that the effect of γ the ratio of specific heats, was small). It was also decided to examine the theoretical and experimental information on the expansion of free jets to aid interpretation of the model results.

Finally a rifle was mounted on a ballistic pendulum and used to substantiate the steady flow results. Full scale tests on a few of the recommended brakes are in hand to check for any possible scale effect.

Theoretical considerations

The conventional flow pattern for an underexpanded sonic jet is given in fig. 1 It is seen that, within the boundary of the jet there is a shock surface joining the sonic nozzle to a normal shock - the Mach disc. This is often referred to as the shock bottle, and for most practical cases muzzle brakes lie within the confines of the shock bottle. The flow inside the shock bottle was investigated by characteristics methods by Owen and Thornhill (ref. 2) in 1948. They were the first to point out that the solution within the bottle is a universal one and not affected by external pressure, although, of course, the extent of the universal flow is limited by the shock bottle size which is determined by external conditions. They gave the axial distribution of variables within the bottle (fig. 2).

More recently, Sherman, 1963 (ref. 3) used characteristics solutions to produce an empirical relation for the radial variation of variables and Thornhill, 1965 (ref. 4) has produced a similarity solution for the far field flow giving radial distributions (fig. 3).

The geometry of the jet boundary and shock bottle has been investigated experimentally by Love et al (ref. 5), Bier and Schmidt (ref. 6) and Vick et al (ref. 7).

From all these sources it is possible to obtain a fairly good idea of the distribution of pressure and momentum within the shock bottle and of the dimensions of the shock bottle and jet boundary for the pressure ratios applicable to the muzzle brake operating range and for the region close to the muzzle of a gun. With this information we can consider the following simple model.

Suppose a flat disc with a central hole, simulating a simple muzzle brake, is placed on the axis of a free jet at, say, 1 calibre from the nozzle. If we suppose that the surface of the disc either absorbs all the gas which would otherwise pass through its boundaries or deflects this flow away normal to the axis without disturbing the external flow, then it is possible to calculate the thrust which would act on this surface. We will define the fraction of the total thrust acting on the surface as η, which may be regarded as an Aerodynamic Index and it is equal to (momentum destroyed by brake) $\div$ (total gas momentum). Thus

$$\text{Recoil momentum} = \text{shot momentum} + \text{gas momentum } (1+\eta)$$

$\eta = 1$ is equivalent to complete deflection of the jet through 90° and $\eta = 2$ is the maximum possible value when all flow is completely reversed.

Now as the pressure ratio $\overline{p}$ is increased ($\overline{p}_o$ = stagnation pressure divided by ambient pressure) the shock bottle and jet boundaries expand (fig. 4). At first, if the central hole is equal to or greater than the nozzle diameter, all the flow will pass through the central hole giving a zero value to η (point A on fig.5). Then as $\overline{p}_o$ increases the jet boundary and then the shock bottle will expand until they both meet the surface of the disc. The flow through the central hole is now fully established and the thrust corresponding to this flow will not be affected by further pressure ratio increase. Thus η equals unity less the thrust fraction lost through the central hole. This is shown by point B in fig. 5. Further increase in $\overline{p}_o$ leads firstly to the jet boundary passing around the outside of the disc (point C) and secondly to the shock bottle escaping around the disc (point D). The flow is now fully established over the whole disc and η equals the thrust fraction over whole disc less the thrust fraction over central hole. Further increase in $\overline{p}_o$ will not alter .

The picture will change at a different axial position. For example, at 2.5 calibres from the nozzle ($\overline{x} = 2.5$) the diagrammatic relation becomes the dotted curve of fig. 5. It is possible to relate η to $\overline{x}$, and fig. 6 shows the curve for the same case for large pressure ratios where the flow is fully established.

As will be seen later this simple model gives a close fit to the experimental results and we are now able to make some deductions relevant to the design of muzzle brakes.

Firstly, the $\eta - \overline{x}$ curve (fig. 6) shows an optimum position for a given baffle. This arises from the combination of the loss of flow through the central hole which decreases with $\overline{x}$ and the loss external to the disc surface which increases with $\overline{x}$.

Secondly, the disc is more efficient at low (and unpracticable) values of $\overline{p}_o$ than it is at larger values of $\overline{p}_o$, typical of those prevailing during the outgassing of a gun barrel.

From the above observations it follows that a good muzzle brake could be achieved by

(i) placing the central hole as far from the muzzle as possible,

(ii) placing the outer boundary as close to the muzzle as possible,

(iii) extending the barrel with a shaped end designed to constrain the flow and simulate the shock bottle shape at the highly efficient low values of $\overline{p}_o$. (This can only be partially achieved since a gap must be left for the flow to escape from the disc).

Considerations (i) and (ii) imply that the brake surface, instead of being flat, should be "dished", that is, it should be a truncated conical surface with the larger diameter nearer to the muzzle. The angle θ is then defined as the angle between the cone generator and the normal to the cone axis. A zero value for θ thus defines a flat disc.

This shape has two further advantages:

(a) Such a shape presents a surface roughly normal to the expanding jet streamlines, giving rise to a strong normal shock. The subsequent subsonic flow appears to be readily deflected outwards.*

(b) Arising from (a) the flow is directed more to the rear. This suggests that the simple theory can be extended to give:

$$\eta_\theta \doteq \eta_{\theta=o} (1 + \sin \theta)$$

Experiments substantiate this flow model up to values of θ of 60^o.

Consideration (iii) is achieved by extending the barrel with a shape based on the jet boundary at $\overline{p}_o = 10$ which corresponds to the peak efficiency shown in fig. 5. The gap between the extension and the surface varied in the model experiments but a gap of at least 0.5 calibres was desirable.

Earlier theories were based on a series of turning vanes and on the escape area between the vanes. A single turning vane is found to be inefficient since the flow on the concave surface tends to separate between the leading and trailing edges, resulting in a small turning angle. The use of multiple vanes increases the efficiency.

When the brake surfaces or the barrel extension seriously impedes the escaping flow then the escaping area becomes important and the simple theory explained above must be modified.

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*This was deduced from some unpublished tests in a shock tube with side duct by N.B. Wood, R.A.R.D.E.

Experimental results

Most of the experiments were made on the rig shown in fig. 7 in which a free jet at 100 lb/in gauge, exhausted into an evacuated chamber at pressures down to a few millimeters of mercury. The supply air was ducted to the rig through flexible joints and the reaction of the floating rig could be measured on a spring balance. Tests with and without baffle surfaces enabled values of η to be obtained.

Results of model tests on a flat disc of 2.0 calibres outer diameter and 1.125 calibres inner diameter are shown in fig.8a and compared with the theoretical results described above. It will be seen that the agreement is remarkably good even at the points A,B,C,D of the theoretical model. Fig. 9 compares theory and experiment for a dished surface, varying $\overline{x}$; again the agreement is good.

The distribution of pressure over a few typical baffles was measured for some values of $\overline{x}$ near the optimum position. A typical result for the pressure loading on the surface is given in fig. 8b. First, the integrated load matches the thrust measurement closely, as it should. Second, the distribution at low pressure is consistent with the theory of the movement of the shock bottle over the surface.

A wide range of models were tested covering variation of inner diameter, outer diameter, $\overline{x}$,$\overline{p}$, θ and barrel-extension shape. In addition, cowled brakes, pepper-pot brakes, slotted barrels and the effect of brake support were all examined experimentally and the theoretical model extended to cover these cases. For models of multiple baffle surfaces the optimum position for the first surface was found and then a second, and subsequently a third, surface was added and optimised. Results for a brake of 2.5 calibres OD, 1.125 calibres ID and $\theta = 40^\circ$ are shown in fig. 10. From a large number of such tests the curves of fig.11 and 12 could be obtained summarising the optimum for that particular type of brake. In all, some 500 brakes were tested in a 3-month period which is a good indication of the usefulness of the model testing technique.

Some additional tests were made with a 7.62 mm service rifle mounted on a ballistic pendulum and the recoil was measured with and without brakes. A few of the brake designs were chosen for the tests and a comparison is shown in the table below.

Comparison of values of η derived from steady flow experiments and those derived from tests on a 7.62 mm rifle

No.	Description	η from rifle	η from steady flow*
1	Flat brake	0.48	0.49
2	Dished brake (θ=20°)	0.69	0.67
3	Ditto with barrel extension	0.69	0.72
4	As 3 with 2 baffles	1.00	1.02

*Averaged for $\overline{p}_o$ = 100 to 500

The agreement is very good, indicating that the assumptions made about η and steady flow were justified.

A short series of full-scale tests are planned to give information on other model scale effects.

Blast experiments

A 7.6 mm rifle was used to determine the blast distribution around a gun. After preliminary experiments with a transducer it was decided to use a spark source to obtain the blast wave shape and velocity from which the local overpressure could be deduced. Figs. 13a-d shows some typical instantaneous photographs of blast waves. The effect of muzzle brakes on the pattern is very noticeable.

Fig. 14 shows some typical distributions of overpressure deduced from these results. Interpretation of these distributions depends on the position of the observer, but to illustrate the practical application, values of overpressure close to the breech, have been considered, and the position near the breech where the overpressure is 2.5 psi (17% of atmospheric pressure) deduced. This position has been plotted against η for the brakes tested fig. 15. Of course the distance from the muzzle increases with η for all types of brakes. However some designs are less noisy than others for the same efficiency.

These conclusions would of course be quite different for other crew positions e.g. the crew of a neighbouring gun.

Conclusions

The object of these model tests was to supply the designer with a consistent parametric study of the muzzle brake problem. This object was achieved together with a theoretical explanation based upon a simple theoretical model and this should enable the experimental results to be extended to future designs without the necessity of resorting to further experiments.

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Item 4 Experimental Full Calibre Firings G.R. Nice, B2/R.A.R.D.E.

Introduction

This presentation is an attempt to link the model studies described in the previous paper with the practical designs to be discussed in the next. It will be a brief account of full calibre firings made by the Ballistics Branch of R.A.R.D.E. at Woolwich in confirmation of the model work and in the course of other experimental investigations.

Experimental

In our firings the prime quantities measured have been the blast distribution around the gun and the efficiency of the brake in reducing recoil of the gun.

For the blast measurement we have used the foil gauges already discussed at some length. The efficiency of the brake is measured using a "free recoil mounting" very similar to that described in item 2. This consists of a pair of fairly massive horizontal rails on which a wheeled trolley carrying the gun can run. The gun is fired with the trolley carriage pushed forward and it recoils virtually freely along the rails for ten feet or so until arrested by a buffer pad connected to a hydraulic energy absorbing system (fig. 1).

Recoil velocity is measured from a high speed framing camera record, which also shows flow of gases from the muzzle, and by a magnetic pick-up device in which a magnet fixed to the recoil trolley passes near to a number of fixed coils; the voltage induced in the coils is recorded on a cathode ray oscilloscope fitted with a drum camera. A close up view of the gun in the mounting is shown at fig. 2.

The system has been used with a variety of guns ranging from a 6 pr gun, calibre 57 mm, to a Naval 4.5 in gun. The former has been used for the majority of experimental studies.

The theoretical aspects on muzzle brakes will not be discussed in detail but some indication of the methods, used in analysing results may be helpful.

Muzzle brake efficiency is quoted as a reduction in recoil energy from the formula defining the intrinsic efficiency, E,

as $$E = 1 - \frac{\text{wt. of gun and brake}}{\text{wt. of gun}} \times \frac{\text{recoil energy with brake}}{\text{recoil energy without brake}}$$

We have also used a coefficient B defined as

$$B = 1 - \frac{\text{post ejection momentum with brake}}{\text{post ejection momentum without brake}}$$

E and B are related by the expression $E = \alpha B\ (2-\alpha B)$, where α is the ratio of post-ejection momentum to total momentum,

α may be calculated from

$$\alpha = \frac{KC\sqrt{RT_e}\ (1 + C/12W)}{(W + \frac{1}{2}C)\ V + KG\sqrt{RT_e}\ (1 + C/12W)}$$

where C = Charge weight
W = Shot weight
R = Gas constant
T_e = Mean gas temperature at shot ejection
V = Muzzle Velocity
K is a numerical constant depending on γ the ratio of specific heats of propellant gases for $\gamma = 1.25$ $K = 1.35$

This formula is obtained by calculating momentum using simple Hugoniot theory. This is much simpler to apply than other more sophisticated theories (e.g. Rateau and Corner) and is not inferior as in accuracy with regard to total momentum though it under-estimates momentum flux initially and over-estimates it finally.

We have obtained good agreement for practically measured and calculated values of B for values of C/W up to about 0.5 after which the Hugoniot theory tends to brake down and this gives confidence in the theoretical predictions of the performance of various brake configurations.

Results

A wide variety of brakes have been fired, some are shown in figs. 3a and b and they have included experimental high efficiency designs, where almost complete recoillessness has been achieved, full calibre versions of model brakes and brakes, with and without additional attachments, designed to reduce blast in the crew area of a field weapon.

The full calibre versions of the model brakes (figs. 4a and 4b) have given very good agreement with the small scale results. Comparison of full calibre and model brakes is somewhat involved because of the need to introduce scaling corrections for all factors charge weight, shot weight calibre etc. and to adjust for necessarily different propellant parameters. When all this is done a typical result is that a model brake for which $\eta = .76$ at $\overline{p} = 500$ gave $\eta = .73$ at $\overline{p} = 870$ in a full calibre experiment.

It is felt that sufficient data is now available to enable a brake to give virtually any efficiency required in a specific case to be designed.

Attempts at producing high efficiency without the increase in blast at crew stations which normally results from the rearward deflection of gases have not been so successful.

Attempts to confine the deflected blast temporarily to slow down the gases so as to eliminate the shock front have failed almost completely (fig. 5).

The most encouraging results have been obtained with a very simple type of fitment, the Pepperpot (fig. 6) which has given worthwhile efficiencies 40-50% without much increase in blast.

SESSION II - DEVELOPMENT

Item 1 Experimental Muzzle Brakes P.B. Shilstone, B1/R.A.R.D.E.

I would like to start by outlining the history of muzzle brakes as seen from this country.

Ever since the first gun was made, some time in the 14th century, there has been a continuous quest to throw heavier projectiles to even greater ranges from lighter and more mobile equipments.

Many problems had to be solved with regard to the better control of gunpowder and the manufacture of guns to withstand higher pressures.

By the 19th century, another problem was becoming apparent - namely that of recoil. There is a record of this being a nuisance in warships as early as 1689. The equipments of those days were allowed to run backwards when fired, which meant that they had to be manhandled into position before firing the next round. In 1815, at Waterloo, it was recorded that the gunners were so fatigued by this chore that theybbecame unable to relay their guns.

I think it is interesting to observe that the problem of recoil was first tackled at its source by the invention of the muzzle brake, rather than by attempting to devise a recoil system.

In fact, in the Rotunda Museum at Woolwich, a bronze 9 pr, 13½ cwt gun is shown, the chase of which is drilled with 30 x 1½ inch rearward facing holes set at an angle of about 45°. It is said to have been used in an experiment in 1862, the results of which showed that although recoil was reduced, there was also considerable reduction in velocity and range, and mention of crew discomfort.

In the same year, the French, persuaded by Colonel Beaulieu, carried out much more successful trials with a 160 mm naval gun, having 36 holes, 60 mm in diameter, also inclined at 45° to the rear. A 75% reduction in recoil was reported, with a loss in muzzle velocity of only 1/16th - the accuracy was said to have been doubled.

However, no general use of muzzle brakes was made until after perfection of the recoil system. This was achieved by the German engineer, Haussner, in 1888, and successfully applied by the French to a 75 mm field gun in 1897.

It was soon realized that although the "buffer-recuperator" recoil system allowed the forces on the carriage to be kept within reasonable limits, the price of greater reduction in forces was - increased length of recoil and increased equipment weight. For a given gun there is an optimum length of recoil for minimum size and weight of the whole equipment.

Weapon designers then returned to the idea of the muzzle brake to assist in their continuous quest for higher performance from higher equipments.

So it was, that from about 1888 onwards, designers produced a vast multitude of various designs of muzzle brake.

From the theoretical stand-point, the physicist Hugoniot published a paper in 1886, dealing with flow of gases from an infinite container. This was an important landmark, and most subsequent theoretical studies have Hugoniot's work as a basis of investigation.

During the first World War, the French took a keen interest in muzzle brakes, and after the war they invited A. Rateau, the thermodynamicist and steam turbine designer to study the problem. The result was the first comprehensive paper on the subject, containing theories and formula for design, which, except for some slight changes, are still in use.

Rateau applied the basic principles of convergent-divergent nozzles to muzzle brakes, departing from the type of design then current, which amounted to an annular plate placed around the path of the emerging projectile.

In 1918, Galliot and Bory of France, produced a muzzle brake on Rateau's principles, which was reported as being highly efficient, and under certain circumstances, capable of eliminating recoil. The work of these men continued throughout the inter-war period. As late as 1943, trials in this country were carried out with a GALLIOT BRAKE on a 17 pr anti-tank gun. The results showed a reduction in recoil energy of 81%, but excessive back blast occurred, and the brake failed mechanically after only a few rounds had been fired.

During World War Two a great deal of work was carried out in Germany, notably by Oswatitsch, at the Kaiser Wilhelm Institute of Flow Research at Gottingen. This was based largely on a series of the excellent "Schlieren" photographs, showing gas flow through model muzzle brake configurations. Although the models were only two dimensional, and the gas velocities relatively low, (up to Mach 1.17) the work indicated the importance of shock waves and claimed advantages for certain baffle shapes. During this period large numbers of different designs were manufactured and tried. The two-baffle brake chosen for the 17 pr anti-tank gun is an example of one of these German designs adopted for British use.

The standard British design methods, which are due to Corner and others, date from 1942, and are based largely on previously existing theories, such as those of Hugoniot and Rateau. The most important simplifying assumptions made by these investigators, and embodied in these standard methods are:-

(i) The gun acts as a convergent-divergent nozzle, with a throat area equal to that of the bore.

(ii) The effect of shock waves in the gas can be neglected.

(iii) That the state of flow at any instant, is the same as that which would be set up in a steady flow, with the reservoir pressure existing at that instant.

(iv) That the effect of co-volume can be corrected for by a factor.

A great deal of attention was paid to this subject by Britain during World War Two, and a good example of British work of that time is the so called 3 G turbine type "Streamline" muzzle brake, developed jointly by Mr. C. Gibbs, (later Sir Claud Gibbs), Dr. C.L. Guy and Dr. H.J. Gough, in conjunction with the Gun Design Committee. Although brakes of this type were found to give the high efficiencies of the complex Galliot version, they also suffered from excessive back blast. (Probably 12-15 psi in the crew positions). In addition, they proved to be somewhat unreliable mechanically, were difficult to manufacture and were extremely heavy.

Fig. 1 shows some typical designs of that period, and indicates their gross EFFICIENCY, which may be defined as the percentage reduction in free recoil energy which occurs when the brake is attached to the recoiling mass. On these terms, aerodynamic or momentum performance, which is the object of all designs, is apparently enhanced by the dead weight. With the heavier designs this amounts to some 5% at 85% and increases for lower efficiencies to about 10% at 70%. As a dead weight alone some could achieve about 20% gross efficiency.

Modern muzzle brake design in this establishment is backed up by practical work in which efficiency is measured by means of a free recoil trolley, which facilitates direct measurement of maximum velocity of free recoil. It is then a simple matter, from readings taken with and without the muzzle brake, to deduce the percentage reduction in free recoil energy due to gas action. This is the definition of Intrinsic Efficiency. If no correction is made for the additional mass of the brake, then the term "gross efficiency" is used.

Momentum index B can also be deduced from free recoil trolley results, using the relationship that:-

Total momentum of free recoiling mass -------(1)

= (Momentum added up to shot ejection ---------(2))

+ (Momentum added after shot ejection without a muzzle brake x (1-B) ---(3)).

(1) Total momentum of free recoiling mass, = Recoiling mass x maximum recoil velocity.

(2) From empirical formula, momentum added up to shot ejection = ($\frac{1}{2}$ charge mass + projectile mass), (muzzle velocity).

(3) By subtracting (1) from (2) we obtain the momentum added after shot ejection, or in other words (3) the momentum added after shot ejection without a muzzle brake x (1-B).

Therefore Momentum Index B =

$$1 - \frac{\text{Momentum added after shot ejection with brake.}}{\text{Momentum added after shot ejection without brake.}}$$

The Momentum Index B is intended to be a constant solely dependent upon the geometry of the muzzle brake.

The normal requirement is that a muzzle brake shall be light, strong and simple to manufacture. This, together with limitations imposed by back blast, means that very high efficiencies are not practicable, and moderate values, in the region of 20-40% have had to be accepted. Nevertheless, this represents an appreciable reduction in recoil energy, and is very welcome to the mounting designer. A good example is the two-baffle design used for the 105 mm ABBOT gun, giving a modest efficiency of about 40% at supercharge.

During the development of the ABBOT muzzle brake, the experimental muzzle brake shown in figs. 2a and b was produced. This was nick-named the Umbrella Brake, and is of interest because it served to underline difficulties in the application of momentum index, and also because it achieved exceptionally high intrinsic efficiencies. It fitted two guns of totally different character, namely the Abbot field gun, with a charge to projectile weight ratio of about 1 to 5 and a 105 mm Tank gun using a ratio approaching 1 to 1. When fitted in turn to these guns, the intrinsic efficiencies were 58% and 88% respectively, but the measured momentum index, which should have remained unaltered, was 1.84 and 2.94 respectively. The need for a more consistent measure of performance was now apparent.

I think it is interesting to note that up to this time, efficiencies of over 80% had only been thought possible with smoothly stream-lined brakes, such as those of Galliot or the three G's.

An entirely new light has recently been thrown on muzzle brake design by the three dimensional model testing work, carried out by D4 branch of this establishment and reported in Session 1, Item 3. Good correlation is being obtained with full scale brakes together with a useful guide as to the back blast which can be expected.

A most interesting aspect of this work was the creation of Aerodynamic Efficiency, which now provides a true constant, solely dependent on brake design. It deals with the change in total gas momentum brought about by the brake.

The Aerodynamic Index η is expressed by using the relationship that:-

Total momentum of free recoiling mass --------(1)

= (Projectile momentum -----------(2))

+ (Total gas momentum without muzzle brake x $(1-\eta)$ -------(3)).

Total momentum of recoiling mass (1) = recoiling mass x maximum recoil velocity.

Projectile momentum (2) = Projectile mass x muzzle velocity.

By subtracting (2) from (1) we obtain the momentum added by the gases, or in other words the momentum added by the gases without a muzzle brake x $(1-\eta)$.

Where Aerodynamic Index, η,

$$= 1 - \frac{\text{Momentum added by gases with brake.}}{\text{Momentum added by gases without brake.}}$$

$$= \frac{\text{Momentum destroyed by the brake.}}{\text{Momentum added by gases without brake.}}$$

I would like now to point out the differences between these two indices of performance:-

The momentum index relationship, due to the division between before and after shot ejection, leaves a gas momentum term in the expression for momentum up to shot ejection (2), which is not seen by the momentum index term (1-B) in (3). This leads to inconsistencies at higher charge to projectile weight ratios, that is, at higher muzzle velocities, where gas momentum before shot ejection is not negligible.

The Aerodynamic index does not suffer from this difficulty, and will, I am sure, in future provide a much better basis for comparing different full scale muzzle brakes, as well as for interpreting the results of model testing.

However, the distinction between before and after shot ejection momentum is necessary when designing recoil systems, and momentum Index B is used when employing the analogue computer in recoil system calculations. Momentum Index can of course be deduced from the Aerodynamic Index for a given internal ballistic solution. The point being that the Momentum Index varies with the internal ballistic solution, but the Aerodynamic Index does not.

Returning now to the Umbrella Brake.

Although the momentum index varied from 1.84 to 2.94 the Aerodynamic Efficiency remained virtually constant, giving values of 136% and 138% when used with the two different guns.

Current work at R.A.R.D.E. is based on the results of model testing, backed by field trials. A combination of diaphragm and piezo-electric blast gauges is used. The various efficiencies are measured by use of the free recoil trolley.

Experimental brakes for the 105 mm Light Gun are shown in fig. 3. The two-baffle brakes vary in baffle cone angle.

The intrinsic efficiency, momentum index and aerodynamic efficiencies are shown for different charges. All are measured values, but the aerodynamic efficiencies agree within 5% with values deduced from the published model test data. . .

Figs. 4 to 6 show blast over-pressure charts for these light gun experimental brakes for various charges. Fig 7 compares over-pressures for two types with the same charge.

It was from this data, by comparison with figures from existing guns, interpreted by the U.K. Army Physiological Research Establishment, that it was possible to make the choice of the brake C with a baffle cone angle of 40°.

Fig. 8 shows another modern brake, where all round venting is permissable. The aerodynamic efficiency of 93% is again in good agreement with model testing. The intrinsic efficiency is 45%, and momentum index 1.2, but these latter figures would depend on the ballistics of the gun on which it is used.

With tank guns using APDS another problem arises in the form of damage from projectile and driving band components, which discard at the muzzle.

Fig. 9 shows a damaged two-baffle brake. The hole for the projectile had been enlarged to allow passage of the discard, but rubber from a disintegrating driving band component caused this damage.

The actual brake shown has been shaped to alleviate this type of damage, and it now lasts as long as the barrel, - efficiency clearly suffers.

Attempts were made to overcome these difficulties, and a slotted barrel type brake attempted to retain the sabot, while allowing the gases to escape.

An alternative form of "brake" for tank gun use is a perforated barrel. Fig. 10 shows the effect of ½" holes drilled in the barrel - damage is much reduced but model testing results now available, indicate that it would be difficult to obtain a sufficient number of holes for efficiency, without reducing mechanical strength and support for the sabot.

Current work on perforated barrel muzzle brakes, however, does indicate that special designs may be possible with tank guns which could lead to intrinsic efficiencies of well over 50%.

In conclusion, the possibility of muzzle brakes with intrinsic efficiencies of 100% must be mentioned. Such brakes would require high aerodynamic efficiencies combined with high charge to projectile weight ratios. (Figures of the order 160% and say 1.5 : 1 might do). However recoil would still occur, as the gun would have to be retarded by the brake from the velocity achieved at shot ejection. A recuperator is therefore necessary to return the gun to battery. The recuperator, of course, absorbs energy during recoil, so that 100% efficiency is not required, and in fact, the 88% intrinsic efficiency achieved by the experimental Umbrella brake (aerodynamic efficiency 138%) would in fact have been enough to eliminate the requirement for a buffer.

Unfortunately, this ignores two vital factors -

(i) The discarding sabot, which would destroy the brake, and -

(ii) The back blast, which would go a long way to destroying the mounting and any exposed crew members.

As usual the designer can never win!

Item 2 Recoil Velocity Measurement Dipl., Ing., Grubert, F.R.G.

This paper will describe a method for direct measurement of recoil velocity in the study of muzzle brakes. Linear velocity is normally measured indirectly by deduction from time and travel measurements, either by calculation or by some form of mechanical differentiating system. This procedure gives only average velocity between discrete measuring positions and of course involves some analysis.

Direct and continuous velocity measurement has obvious advantages and a system has been developed which can be used with a free recoil stand for measuring velocities of moving parts of weapons and for other similar purposes. The equipment consists essentially of a fixed coil on a coil carrier and a magnet (permanent or an electromagnet) which is fixed to the component whose velocity is to be measured. If possible coil and magnet are so arranged that movement of the component causes the magnetic lines of force to cut the plane of the coil normally and the coil is shaped so that, over the length of travel for which velocity is to be measured induced voltage is proportional to velocity.

If this relative positioning is not possible or if a relationship other than linear between velocity and induced voltage is required, suitable adjustments to the coil windings may be made either to correct for positioning or to achieve the desired voltage/velocity relationship. This equipment is used on the recoil measuring equipment at Meppen described in Session 1, Item 2.

Item 3 Aberdeen Proving Ground technique of gun blast testing and results of full calibre testing in the 155 mm Howitzer, SP, M109 Mr. D Tag, U.S.

Introduction

This presentation will deal primarily with current Aberdeen Proving Ground test techniques and methods as they were applied to some programmes using the 155 mm Howitzer SP, M109 as the test vehicle. The intent is to describe briefly instrumentation available, some typical results obtained and the problem areas that exist.

By way of background, blast testing in one form or another has been carried on at Aberdeen Proving Ground for many years. The majority of these programmes were designed to measure muzzle blast from artillery weapons to determine physical effects upon the material. Some limited testing for physiological effects have been conducted in the recent past for agencies such as the U.S. Army Weapons Command and the Human Engineering Laboratories. Only a very small amount of testing has been done to evaluate muzzle brake design or efficiency. The instrumentation used has ranged from simple, rudimentary paper blast gauges to the more sensitive and precise electronic pressure sensors and transducers.

Instrumentation

There are five basic types of gauge currently in use today at Aberdeen Proving Ground (see Figures 1 and 2).

The first is the Atlantic Research Lab Pencil gauge which uses a ring-shaped lead Zirconate ($Pb\ Zr\ O_3$) sensing element mounted flush with the outer surface about midway down the pointed body. In use, the gauge is directed towards the detonation source and can record only side-on pressure (P_S). The sensitivity factor approximates 1500×10^{-12} coulombs per pound per square inch.

The B.R.L. pancake gauge has a high diameter to thickness ratio as the nickname suggests. The tourmaline crystal sensing element is mounted in the centre of the circular housing. It may be used for either side-on pressure by positioning edge on to the blast wave or for face-on pressure (P_R) by facing the flat sensing area towards the blast. The sensitivity factor is about 30×10^{-12} coulombs per pound per square inch.

The two face-on gauges (B.R.L.) are shown as items 3 and 4 in Figure 1. The first was developed to record velocity through sensing arrival time of the shock wave at two or more positions. These are used principally for calibration of the pencil or pancake gauges, but may also be used for direct pressure measurements. The barium titanate ($Ba\ Ti\ O_3$) sensing element is mounted in the forward section of the tubular housing and has a sensitivity factor of about 5×10^{-12} coulombs per pound per square inch.

The second face-on type is a smaller impulse-loading gauge designed especially for flush mounting on surfaces such as engine compartment doors. It is used to record blast loading data and has a quartz crystal sensing element with a sensitivity of 10^{-15} coulombs per pound per square inch.

Finally, the foil gauge shown in Fig. 2 is an adaptation of the United Kingdom modified Adams gauge described earlier in Session 1. We manufactured the gauges locally from drawings furnished by the U.K. and used the "cigarette" foil also supplied by them. This gauge proved useful for obtaining approximate ranges of pressure in confined areas where reflected shock wave conditions rendered the more sophisticated electronic gauges virtually useless. At least electronic data was always highly suspect.

Calibration of all the above gauges was routinely performed before and after each major test firing series. This is a fairly straight forward procedure using bars spherical charges of pentolite in weights known to give pressure levels close to those anticipated for the actual test. For the 155 mm Howitzer programme, 8-pound charges were used with the gauges exposed to the resulting detonation wave.

The actual pressure level at the gauge position is determined by measuring the velocity of the blast wave at that point and computing the pressure by means of the Rankine-Hugonoit equation

$$P_v = \left[\frac{2Y}{Y+1}\right] P_o \left[\left\{\frac{V \pm K}{V_o}\right\}^2 -1 \right]$$

Where:

P_v = over-pressure, psi.

Y = Ratio of specific heats for air.

P_o = Local ambient barometric pressure.

V = Shock front velocity.

V_o = Local velocity of sound thru air.

K = Wind correction.

The gauge described above is used for this purpose. Additional information is available in reference 2.

The array and types of gauge used in any given programme is naturally determined by the test objectives. Figure 3 shows a typical set-up of pencil gauges around the new 105 mm Howitzer, M102. The purpose of this test was to determine the differences in blast effects at the various crew positions between the two muzzle brake designs. The one shown, incidentally, was similar to the finally accepted design. The other was called the UBU, or upward blast utilizer, which was temporarily dropped from consideration after this test. In testing for physiological effects at crew positions, the accepted practice is to consider only the side-on pressure, hence the selection of the pencil gauges shown in the photo.

When testing for the physical effects upon material, a wider assortment of gauges are used in a somewhat different array as shown in fig. 4. Also shown here are strain gauges at several pre-determined areas of critical stress. This is the instrumentation array used in the 155 mm M109 test, the results of which will be described later.

Fig. 5 shows the array of gauges used in a very recently conducted test of the 155 mm M109 in which the blast over-pressures produced by the U.S. design muzzle brake were compared to those of the F.R.G. design. In the first full calibre test, side-on and face-on pressures were measured by the appropriate gauges. In the second, P_R was computed from P_S. In general, crew occupied positions are measured by side-on gauges while material surfaces such as engine compartment doors and turret hatches use the face-on gauges. Exteriorally mounted pencil gauges are routinely used for control purposes.

Recording the data is usually accomplished with portable trailer mounted oscilloscopes having an 8-channel capacity. The oscilloscope records are displayed on 35 mm film along with the required fiducial and calibration information. More recently a magnetic tape recorder has been used which provides for rapid playback and readout of the data on a round-by-round basis. Galvanometer recorders provide the record and each trailer has up to a 12 channel capacity. This latter equipment was used in the full calibre testing described herein. Frequency response of this system is 0 to 80,000 cycles per second. Tape recording speed used was 120 inches per second while playback speed was 60 inches per second.

Full calibre test and results

The test reported in reference 1 is the primary basis for this portion of the Aberdeen Proving Ground presentation. The test objectives were as follows:

(a) To attempt to establish "threshold" blast over-pressure levels above which vehicular or armament component damage could be expected.

(b) To obtain firing blast-loading data on certain of the more critical vehicle/armament components using both standard (M4A1, Zone 7) and excess pressure (XM119, Zone 8) propelling charges.

(c) Finally, to evaluate instrumentation techniques to determine their validity in predicting component failures and whether a standard array of gauges could be developed for generic tests of all self-propelled artillery designs.

This programme was not intended to establish the relative merits or deficiencies of the M109 weapon system, per se, since this had already been well established in numerous tests at both Aberdeen Proving Ground and the Artillery Test Board. However, the selection of gauge positions was generally based upon these results.

In the above test, 24 data rounds were fired and the tabular results can be readily summarized. Table 1 considers only the maximum muzzle blast over-pressure for each condition of test. The "Adams" foil gauges were used in two locations; one in front of the radiator grille and the other near the engine over-head valve rocker arm cover. The indicated blast over-pressure on both gauges was 2.9 - 3.5 psi when firing the Zone 7, M4A1 charge, regardless of elevation. When firing Zone 8, XM119 charge the pressure range was 7 - 8 psi at 0^{o} howitzer elevation and 4 - 5 psi at 35^{o} elevation.

The maximum principle stresses developed in the various locations about the M109 vehicle are shown in Table 2. Also, a typical strain versus time oscilloscope record may be seen in figure 6. A blast pressure record (P_S) from the pencil control gauge also appears on this chart. Typical face-on (P_R) pressures may be seen in fig. 7 which shows the records obtained at the M109 engine compartment door with the B.R.L. flush-mounted gauge.

While these data were thought to be the best obtainable at the time, all test objectives were not fully satisfied and the techniques used were not considered entirely adequate. The principle reason for this is the vast complexity of the blast over-pressure problem coupled with the lack of instrumentation having sufficient precision and reliability to provide the necessary data. Our experience indicated that it is extremely difficult to obtain precise rate of loading and angle of incidence measurements required to properly analyse all the effects of blast on a fully assembled, complex item of equipment such as the M109. The picture is further complicated by reflected shock waves, duration of impulse and other variables such as component geometry and material properties. One promising approach to this would be to augment the electronic data with photographic techniques as has been done in discrete tests of individual isolated components.

Insofar as developing a threshold blast pressure level and standard gauge array is concerned, only broad guidelines were developed. It appears that blast pressures in excess of 10 psi can be expected to damage vulnerable parts such as radiators, exposed optical instruments and engine components. On the other hand, heavier components such as engine hatches and armour plate withstood pressures in excess of 100 psi.

While no single standard array was evolved for all vehicles it should be readily possible to experimentally establish combinations of instrumentation and locations for any given vehicle design that will produce much valuable design information.

Prediction of component damage likely from a given level of blast pressure alone appears to be virtually impossible since this would depend on other factors that we have so far not successfully measured. These include the rate of pressure application, the resulting resonance imparted, stress limits of the materials and their configuration.

Some interesting anomolies were noted in this programme, however. One is shown in Fig. 7 where the total duration of P_R on the engine compartment door was significantly longer for the higher pressure XM119 charge than for the M4A1 Zone 7 charge at both high and low elevation. These might have been explained had we been able to measure shock wave velocity at that point. Gauge "ringing" as a result of resonance in the cover material which differed in amplitude and duration because of variations in the severity of initial shock is another possibility.

The comparison test between the U.S. and F.R.G. muzzle brake designs for the M109 conducted at Aberdeen Proving Ground considered blast over-pressure at predetermined positions as well as recoil time/pressure and trunion reaction characteristics. Reduction of this latter data is as yet incomplete and therefore no results or conclusions can be given at this time. However, preliminary results seem to indicate that there is approx. 8-10% difference between the two in either recoil attenuation or trunion reaction forces.

On the other hand, the peak blast over-pressure data clearly indicate that the F.R.G. design produces significantly lower pressures at the on-board gauge positions than does the U.S. design. The pencil control gauges off-vehicle show no real differences in the pressure levels. Tables 3 and 4 summarize the results at both 0° and 70° quadrant elevation respectively. As in the earlier test, the XM119 type charge was used to produce excess pressures. The double sets of numbers separated by a slash (/) show both peak pressures in those instances when two peaks were clearly discernable on the pressure/time trace.

In summary, blast data from full calibre testing can be successfully acquired that will satisfy many weapon design requirements and certain useful parameters can be established. Further development is indicated in both instrumentation and techniques to deal with rates of loading, reflected shock waves, negative pressures and to permit discrimination between these phenomena as they effect component strain and distortion.

References

1. Nelson, R.H. Special Study Test of Damage from Self-Propelled Weapon Muzzle Blast. (Technique and Study Programme) DPS-2238, Feb. 1967.

2. USATECOM Test Procedure 700-700 Series, Interim Phamphlet 80-12.

Item 4 <u>Empirical studies on the reduction of muzzle brake blast</u>
Mr. M.J. Salsbury, U.S.

At the present time, Rock Island Arsenal is about a third of the way through a study of blast reduction. In this study, our general approach has been to isolate each muzzle brake parameter and empirically determine its effects on both back blast and efficiency.

Problem

To briefly summarize the problem, the efficiency of a muzzle brake is dependent upon the quantity, velocity, and exit angle of the muzzle gases it deflects. However, these same factors also determine the amount of gas directed toward the gun crew, and, as a result, the severity of the blast effects on the crew is usually proportional to the brake's efficiency. The problem, then, is to reduce these blast effects without compromising brake performance.

Criteria

Before discussing the studies we have already completed, I would like to define the criteria we applied to the terms "efficiency" and "blast effects". The efficiency rating we use in all our brake studies is the momentum index, which is the ratio of the impulse imparted to the brake, to the impulse imparted to the gun, during the gas ejection period. As to the nature of the blast effects, it is generally agreed that it is the excessive over-pressures, rather than the blast wave's total positive impulse, which is most injurious to the crew.

Approach

Using this criteria then, our approach to the problem was to lower the peak over-pressures of the shock wave by spreading its total impulse over a longer period of time. The device we used to accomplish this was a brake reservoir. With this system, the muzzle gases were discharged into a preexpansion chamber before being released into the atmosphere.

Description of model (see fig. 1)

The chamber we used in this study was designed for a 105 mm howitzer and was mounted on an adapter tube, attached to the muzzle. In order to regulate the flow through the system, several parameter variables were provided. The chamber's volume could be adjusted by positioning the rear end-plate and had a range equivalent of from 1 to 2-1/4 bore volumes.

The chamber's entrance ports could be varied by rotating the port collar and aligning the slots in the collar with those in the adapter tube. The exit ports could be adjusted by the positioning of the baffles. Both sets of ports had a range equivalent of from 0 to 3 bore areas.

Test equipment (see fig. 2)

The reservoir was tested with a 105 mm howitzer tube mounted on a free recoiling test fixture. The recoiling portion of this system weighs approximately 2600 lbs., and rolls on small cam follower bearings confined within the channels of the base mount. About 5 feet of free recoil distance is provided before the recoiling mass is stopped with crushable cardboard.

In order to determine the brake's impulse, the reduction of recoil velocity it has produced by the end of the gas ejection period must be known. Rather than using the interior ballistics equations to determine this point in time, we, instead, fired the system without a brake attachment and recorded the time at which the maximum recoil velocity occurred. We then used this as a point of reference throughout the study. (See fig. 3).

The recoil velocity was measured with a magnetic pickup attached to a rack and pinnion gear arrangement. The data was recorded on an oscillograph into which a timing generator was also channeled.

To determine the projectile impulse, the muzzle velocity was measured by firing magnetized projectiles through two copper coils. The resulting impulses were then used to start and stop an electric counter.

The over-pressures were measured with piezo-electric pencil gauges and recorded on an oscilloscope with a polaroid camera attachment. Of the four gauge locations shown here, the results obtained at the two furthermost from the muzzle, are those which will be discussed.

Procedure

As for the procedure followed in this test, the initial firings were made with the chamber's entrance port closed. In doing this, the brake reservoir becomes passive and the total impulse on the recoiling parts can be determined. By subtracting from this value the impulse imparted during the in-bore period, which is equal and opposite to the projectile's impulse, one can calculate the impulse imparted during the gas ejection period.

During the balance of the firings, three combinations of entrance and exit port areas were tested, and for each combination, the chamber's volume has varied over its full range in six, 1/4 bore volume increments.

Results (see fig. 4)

The test results are shown here in a graph on which crew area over-pressure is plotted versus chamber volume, for each of the three port configurations. Since the system's efficiency varied with port area changes, the momentum index is also designated for each configuration. These efficiency values did not fluctuate with volume, however, indicating that the volume changes were only affecting the duration of the brake's gas flow, not its magnitude.

For the first run with both sets of ports wide open, the momentum index was .97. For the second, with the exit ports equal to 1-1/2 bore areas and the entrance ports equal to 3, the index was 1.06, and for the third, in which both sets of ports equal to 1-1/2 bore areas, a value of .8.

Looking at the over-pressure results, you can see that for each run, peak over-pressure in the crew area drops as the volume of the expansion chamber increases. The attenuation rate was approximately 2 psi per bore volume.

From the viewpoint of the efficiency-over-pressure relationship, this method seems ideal in that it provides a 30 to 40 percent decrease in over-pressure with no subsequent loss of efficiency. Unfortunately, however, the trade-off between over-pressure reduction and weight is very poor. With an attenuation rate such as this, any brake relying on volume alone to lower over-pressure substantially, would be much too large to be practical.

Another aspect of the results, however, did show some promise. When comparing runs 1 and 2, one can see that the 50 percent reduction of exit port area caused an even greater over-pressure drop than did the full expansion of the chamber's volume. This is true for every volume setting, and, as you can see, there was no significant change in the momentum index.

When initially planning this test programme, we knew that the exit area would certainly influence mass rate of flow, but we also expected a proportional loss of efficiency. As a result, not much data was taken in this area and further testing of port areas must be done.

As for the third run, in which both sets of ports were half closed, the over-pressures were essentially the same as those in run 2, but accompanied by a sharp drop in the momentum index. This drop in efficiency can be explained by the fact that ratio of the extrance port area to the muzzle area is now much smaller, and, as a result, more gases are exiting from the chamber's projectile port. (See fig. 5).

To provide some type of raw performance comparison, two conventional brakes were also tested and the results are shown here with run 2. The top line represents a modified 5K brake having a momentum index of 1.15 and a peak crew area over-pressure of 4.5 psi. The lower line at 3.5 psi represents the M2A2E2 brake which is rated at .97. As you can see, up to about 1-3/4 bore volumes, the proportionality of the reservoir's efficiency to over-pressure is in line with those of conventional brakes, but has an increasing over-pressure advantage as the volume is increased.

As to whether or not any reservoir system can be optimized to out-perform conventional brakes without suffering an impractical weight penalty, is impossible to say at this time. Not only is more testing needed on port areas, but more importantly, the effects of the baffle parameters on back blast and performance must be taken into account.

We have already completed some testing of baffle parameters which brings me to the next study I'd like to discuss. The object of this particular study was to determine what effects the brake's baffle diameter and downstream location had on over-pressure and efficiency.

Test model (see fig. 6)

The brake fixture used in this study consisted of three flat discs having outside diameters of 15, 20 and 25 inches, and projectile port diameters of 4-1/4 inches. These discs were attached by four rods to a muzzle collar and could be positioned anywhere from 0 to 15 inches from the muzzle with spacers. This model was scaled up from one used in a similar study done with small calibre weapons.

<u>Procedure A</u> (single baffle)

The discs were tested in single, double, and triple baffle combinations, using the same test mount and instrumentation methods as in the previous test.

During the single baffle phase, each disc was tested over the full downstream range in 5, 3 inch increments.

<u>Results A</u> (single baffle) (see fig. 7)

In the upper graph, the momentum index is plotted versus downstream distance for each baffle, and, as you can see, a closely related family of curves exists.

As each disc is moved closer to the muzzle, from 15 to 9 inches, the efficiency gradually increases. Moving each disc still closer, the momentum index for each reaches a maximum value somewhere between 9 and 6 inches, and then begins to gradually decrease. You can also see that the larger the disc, the further downstream its maximum efficiency occurs. In the remaining region, upstream from the 6 inch location, the efficiencies of all discs drop rapidly and approach a common value.

Sets of curves similar to this can be found throughout the literature in one form or another, and their explanation is this: as each disc is moved upstream, less muzzle gas escapes around it: the larger the disc, of course, the smaller the loss. The somewhat level portion of the curve, between 9 and 6 inches, indicates this to be a region in which the gases, escaping through the baffle's projectile part, become more appreciable, and offset the decreasing gas loss around its periphery. As a result, the brake's net impulse is kept nearly constant. When this trade-off is at an optimum, the maximum efficiency of the baffle is attained. As the baffles are moved still closer to the muzzle, the projectile port becomes the predominant escape route and efficiency begins to drop. Further upstream, a point is reached at which gass loss around the periphery of even the smallest disc ceases to occur, and all the baffles will deflect the same amount of gas.

The performance of the 5K and M2A2E2 brakes have again been shown here and on the rest of the graphs, merely to provide points of reference.

Looking now at the over-pressure results in the lower graph, you can see that as each baffle is moved upstream, over-pressure in the crew area rises, and peaks somewhere between 0 and 3 inches from the muzzle which we know, from the first graph, to be a region of low efficiency. It should be noted also that over-pressure is little effected by baffle diameter.

<u>Procedure B</u> (double baffle)

In the second phase of the programme, in which double baffle combinations were tested, the same basic procedure was follows. The first baffle, that closest to the muzzle, was always placed 6 inches downstream and the locations of the second baffle were varied.

Results B (double baffle) (see fig. 8)

In the upper graph, the momentum index is plotted versus the distance between the first and second baffles, and the results are similar to those of the first phase. Maximum efficiency occurs in the region between 9 and 6 inches, drops rapidly between 6 and 3 inches, and from 3 to 0 inches, contributes nothing at all to the efficiency already gained by the first baffle.

The same explanation as before holds true here. Most of the gases passing through the projectile port of the first baffle also pass through the second, unless the discs are at least 6 inches apart. You will also notice that regardless of the size of the first baffle, the efficiency gained by the addition of a second baffle is always the same. Again, this would indicate that no gas is flowing around even the smallest second baffle.

Looking at over-pressure results, you can see that the data does not follow the same pattern as that of the single baffles. Instead of over-pressure rising as the second disc is moved closer to the first, it simulates the efficiency curve. The reason for this is that the gases being deflected by the second baffle are being directed away from the crew by the first. This channeling effect becomes stronger as the two baffles are moved closer together, and, as a result, when the discs are less than 3 inches apart, all these gases are deflected at a 90° angle and do not reinforce the shock wave created by the first baffle.

Procedure - Results C (triple baffle)

In the last phase of the study, we tested triple baffle combinations. The results of this phase can be summed up by saying that the addition of a third baffle produced by no measurable effects on either the efficiency or over-pressure.

Conclusions

The conclusions which may be drawn from this overall study fall into three categories: first, the effect of the baffle's diameter and location on efficiency: second, their effects on over-pressure, and, lastly the relationships between over-pressure and efficiency which are caused by these parameters.

1. As for the effects on efficiency, nothing, of course, was discovered that is not already a fundamental of muzzle brake theory.

(a) From the shape of the efficiency curves, it can be concluded that for any baffle diameter there exists an optimum location; and, of course, the converse of this is equally true. The exact relationship of diameter and downstream location, however, would vary with the ballistics of the weapon being considered.

(b) From the double baffle test, seeing that any second baffle, regardless of size, produced the same increase of efficiency; it can be said that, if the first baffle is operating at its maximum efficiency, the second baffle need not be larger than the first.

(c) One can see from the double and triple baffle tests that the use of multiple baffles to deflect a higher percentage of the muzzle gases is only practical for two, or possibly three baffles. More than this, and the weight penalty incurred trying to utilize the small amount of gases still available is way out of proportion to the efficiency gain.

2. Considering now the baffle's effects on over-pressure, two conclusions can be made.

(a) First, from the single baffle results, seeing that high over-pressures can be recorded when a brake is operating at low efficiencies, it can be said that peak over-pressures are more strongly dependent upon mass rate of flow from the brake than they are upon the brake's total impulse.

(b) Secondly, since there was no rise in crew area over-pressure, when the first and second baffles channeled the flow to the side of the weapon, we know that over-pressure is a very strong function of the baffle's deflection angle.

3. (see fig. 9)

And now, to illustrate the relationship of over-pressure and efficiency as the baffle location is varied, the results of the 20 inch disc has been chosen as being representative.

Here, the over-pressures are plotted versus the momentum index for every downstream location. As you can see, for the 20 inch disc, the maximum efficiency occurs approximately 7.5 inches downstream, but for every other value of efficiency, there are two values of over-pressure, depending on the baffle's downstream location. Also, for a given diameter, the over-pressure advantage is greatest at lower efficiencies. (See fig. 10).

By superimposing the results of the other two discs on the graph, you can see that the effect that the baffle's diameter has on this relationship is that it extends the range of efficiencies available.

From these facts, it can be concluded that for any baffle diameter, there exists, not only a location of maximum efficiency, but also a location where the optimum compromise between efficiency and over-pressure can be attained. It can also be said that if one is operating along the lower portions of these curves, or, in effect, using locations out past the points of maximum efficiency, one can, by using a larger baffle, increase efficiency without increasing over-pressures.

For example, you can see on the graph that if we choose 3 psi, as an over-pressure reference level, that the momentum index was extended out to a value of about 1.1 with the 25 inch disc. Had we used even larger baffles, placed farther downstream, we could have continued to increase efficiency without exceeding the 3 psi over-pressure level.

Unfortunately, besides being impractical from a weight standpoint, this process of using larger and larger baffles, placed farther and farther downstream, is only effective out to a distance at which the decrease in the muzzle gas velocity limits the efficiency, regardless of what size baffle is used.

It would see, therefore, that these optimum relationships between diameter and location can only be applied practically to muzzle brakes with a low efficiency requirement. But, since it is the brakes of higher efficiencies which cause excessive over-pressure in the crew area, this process, in itself, is not a solution to the problem. It does, however, provide some insight to the problem of finding an optimum brake configuration.

In this same vein of thought, I would like to conclude by reminding you that all these results and conclusions were arrived at by testing these brake parameters in an isolated condition. If and how these relationships are modified when other brake parameters are introduced, we hope to determine in future studies.

Item 5 <u>Muzzle brake design and the reduction of blast</u> Dr. Ing. Kratz, F.R.G.

During the preliminary work for the design of a muzzle brake for the FH 70 155 mm U.K./F.R.G. weapon development, investigations have been made into the possibility of designing a brake which at a given efficiency would result in a minimum of blast in the gun crew area.

The main idea was to design a muzzle brake to meet the following requirements.

(1) The gas deflection angle was to be kept to a minimum.

(2) A maximum amount of gases was to be deflected, so that in spite of the small deflection angle the required efficiency was obtained.

(3) Gases were to be defined in such a way, that at no time during the braking action there would be a greater deflection than that desired.

In addition the brake was to be as light as possible bearing in mind the positive influence of the weight of any muzzle attachment in reducing recoil.

In amplification of (1) above the aim was specifically to keep to a minimum the blast in a cone of semi angle 20° behind the gun and co-axial with the gun. Also in order not to complicate the problem unduly only peak pressures were considered.

The blast pressure behind the gun will increase with the increase in angle of deflection of the propellant gases by a muzzle brake. This is shown in a paper by Schneider "Theoretical investigations on the expansion of shock waves around a gun in regard to blast loading".

The dependence of muzzle brake efficiency σ has been shown by Oswatitsch who derived the formula.

$$\sigma = 1 - \frac{P'_{m_1}}{P_m} \cdot \frac{F_{m_1}}{F_m} + \frac{\bar{w}}{w_{max}} \sqrt{\frac{K^2}{K^2-1}} \left\{1 - \frac{P'_{m_1}}{P_m} \cdot \frac{F_{m_1}}{F_m}\right\} \cos 180^\circ - \phi$$

where P_m = gas pressure at muzzle

P'_{m_1} = gas pressure at front part of muzzle brake

F_{m_1}/F_m = ratio of orifice to calibre area

$\bar{w}/w_{max}$ = ratio of actual emergent gas velocity to maximum possible velocity

ϕ = angle of deflection of gases.

From the above considerations the dependency of blast pressure P_o on brake efficiency σ may be derived.

With low efficiency factors the blast pressure initially rises only slowly. Later the rise is almost constant and considerably greater than at the beginning of the curve. An identical increase in the efficiency factor at low absolute values means therefore a smaller rise in blast than at higher values of the efficiency factor. It is therefore appropriate to keep the efficiency factor of muzzle brakes as low as possible, since with greater efficiency factors the blast increases considerably. This requirement is in line with the use of small angles of deflection.

The Oswatitsch expression quoted above was derived on the following assumptions.

(a) The discharge velocity of the gases at the muzzle is equal to the local sonic velocity in the gases there. This is valid when projectile muzzle velocity is below or equal to this sonic velocity. When projectile velocity is above sonic velocity the assumption is not valid initially.

(b) At the shell exit orifice of the muzzle brake, the velocity is equal to local sonic velocity in the gases present there. This implies that a compression shock occurs on the baffle surface, which reduces the gases in front of the orifice to subsonic velocity.

(c) The pressure of the outward-flowing gases corresponds to the external pressure. If this is not so, then the performance coefficient with the high pressure relationships in question will be only very little altered.

(d) All powder gases flowing from the muzzle of the barrel will be deflected by the same angle, with the exception of the gases flowing through the shell exit orifice.

The dependence of blast pressure on efficiency has been verified experimentally using a variable muzzle brake made by Rheinmetall. Baffles with differing deflection angles were set at different distances from the muzzle and blast values correlated with efficiency.

Returning to item 2 of the initial basic requirements, stated above, which stated the desirability of deflecting as much gas as possible, this was also investigated with the adjustable brake.

By altering the baffle spacings keeping baffle angle constant the amount of gas deflected can be varied.

At a small spacing, much gas flows through the shell outlet orifice without effect, whilst at greater spacings a maximum efficiency factor will eventually be attained. This rise in the efficiency factor is a result of the greater amount of gas from the muzzle brake being used. The blast pressure rises also, although not as sharply as the efficiency factor. The following Table shows the relationship between efficiency factor and blast pressure, first of all with a rebound surface with 126° deflection

Effective value	39 %	47 %	58 %	50 %
Blast pressure	566 mb	530 mb	536 mb	484 mb

At another measuring station and with a rebound surface which had a deflection of 93°, the following relationship was ascertained:

Effective value	19 %	30 %	33 %	35 %
Blast pressure	133 mb	123 mb	125 mb	124 mb

Both measuring stations lay on a line which formed an angle of 15° with the prolonged barrel axis (distance from muzzle 3.5 and 7 m respectively).

Blast pressures were measured with a microphone set normally to a line joining at the muzzle.

These results indicate that blast pressure is not critically dependent on the amount of gas deflected.

Theoretically, this result can be interpreted as follows: the time interval between exit of the shell from the barrel to its passing the first baffle of the muzzle brake is important to the blast pressure intensity. During this time, flow of the gases in a forward direction is impossible, because the shell blocks the outflow orifice. Initially the same amount of gas will be deflected to the side irrespective of the spacing of the first baffle surface from the muzzle. The initial process is therefore critical in determining blast pressure. The subsequent gas flow, which determines brake efficiency, does not significantly affect blast pressure and it is therefore important to deflect as much of the propellant gases i.e. to keep the flow of gas through the shell exit orifice as low as possible.

Finally considering item 3 of the basic requirements, in a comparative firing between a symmetrical round muzzle brake - as is used for the 155 mm M109, for instance - and a type of brake that is planned for the FH 70, it was found that the former generates a higher peak pressure behind the gun. Instead of deflecting surfaces which lie on the surface of a cylinder, the new brake has roof-shaped covering surfaces which permit a much better flow of gases in the desired direction. The round shape gives rise to the generation of backward blast at the upper and lower edges of the brake, which is transferred to the surrounding air giving an increase in pressure. Although the efficiency of the round brake is about 2% higher, due to the greater mean deflection of gases for a short time at the beginning of the process, the greater blast pressure is a decided disadvantage, compared with the brake of the new type of brake. The new brake also has a reduced loss of gases through the front port, since there is no interference with the flow through the baffles in the direction of the front port and since the reduced gas deflection in itself gives a smaller likelihood of reverse flow of gases from baffle surfaces into the shell exit port.

These deductions follow from firings on a free recoil measuring stand. It is felt that it would be useful to give some account of the performance coefficients which are in general use in F.R.G. work on muzzle brakes.

Efficiency is defined as the ratio of the change in recoil energy between firings without and with muzzle brakes and the recoil energy **without** muzzle brake. After an experimental determination of the recoil energy with a recoil measuring rig, the influence of the weight of the muzzle brake is eliminated mathematically. This means that the efficiency is always related to the same recoiling masses (intrinsic efficiency). The velocity of the recoiling mass, necessary for establishing the recoil energy, is determined at the measuring rig as free recoil velocity. Efficiency has the disadvantage of being dependent on the interior ballistics of the gun. In order to eliminate this dependency, the term efficiency factor is used in Germany. The efficiency factor is defined as follows.

$$\sigma = \frac{I_{Go} - I_{Gm}}{I_{Go}} = 1 - \frac{I_{Gm}/m_G}{I_{Go}/m_G}$$

I_{Go} and I_{Gm} represent the total impulse of the propellant gases when the shot is fired without and with a muzzle brake.

Practical experience and theoretical considerations show that the value I_{Go}/m_G; where m_G is the mass of burnt gases or of the powder charge is largely independent of internal ballistic values, such as maximum gas pressure and gas pressure at the muzzle whenever the design of the gun is not too unconventional. This value I_{Go}/m_G can be equated to the mean exit velocity of the powder gases. Tests have shown, that the value I_{Gm}/m_G remains roughly constant when the same muzzle brake is used.

The efficiency factor σ and the efficiency η can be related by the following formula:

$$\eta = 1 - \left\{1 - \sigma \frac{z}{1+z}\right\}^2$$

where the value z represents the ratio $\frac{I_{Go}}{I_g}$, I_g being the impulse of the shell on leaving the muzzle. The value z is therefore dependent on the interior ballistics of the gun. The dependence $\eta = f\ (\sigma, z)$ can be shown in a curve with z for a parameter. From the recoil velocity values obtained at the recoil measuring rig, the efficiency factor is defined as follows:

$$\sigma = \frac{M_{Ro}\ V_{Ro} - M_{Ro}\ V_{Rm}}{M_{Ro}\ V_{Ro} - M_g\ v_o}$$

where V_{Ro} is the recoil velocity without the recoil brake and V_{Rm} the recoil velocity with the brake. M_g is the mass of the shell and v_o the muzzle velocity.

It has already been said that the weight of the muzzle brake cannot be increased arbitrarily. In order to have a light version, the material used must be exploited to its full capacity. This is important, since the forces applied to the gun barrel by the muzzle brake are high. The muzzle brakes produced in Germany since 1945 are mainly made from cast steel. (usually GS-35 Cr. Mo) 104 steel. This material is annealed to a breaking strength of 85 kp/mm², a yield strength of 65 kp/mm² a breaking elongation of 11 per cent. Its notched bar impact strength is 7 kpm/cm² at a temperature of 20 °C.

Muzzle brakes for the 155 mm M109g are made from this steel and are produced by the B.S.I. Company. Very many experiments had to be conducted before a crack-free casting could be produced. This freedom from cracks is most important in view of the very high stressing of the material in use.

Casting non-symmetrical muzzle brakes, such as the proposed FH 70 design presents additional problems but these are being solved.

Forging and welding fabrication methods are also being investigated for muzzle brake production.

Item 6 <u>M109 test firings with U.S. and F.R.G. muzzle brakes and XM119 charges</u>
R.M. Walsh, U.S.

<u>Introduction</u>

This presentation's purpose is to describe the combat vehicle project manager's office experiences when firing the super propelling charge XM119 in the M109.

It will cover the following:-

1. Discussion of general background.

2. Discussion of 2100 round, XM119 charge endurance test conducted in July-September 1966 U.S. muzzle brake.

3. Artillery Board's final conclusions.

4. Discussion of AMC's alternate proposals to extend the range of the M109.

5. Discussion of U.S. V.R.S. F.R.G. blast comparison test conducted in February 1968.

6. Discussion of 2100 round, XM119 charge endurance test conducted in January 1968 F.R.G. muzzle brake.

7. Discussion of long tube approach to extend the range of the M109.

The M109 was type classified on the basis it would exceed the maximum range (14,500 meters) or it's predecessor, the HSP M44A1. Extended range was subsequently achieved through development of the XM119 super propelling charge which was type classified (LP).

A 2100 round XM119 charge test was subsequently conducted by USAARTYBD in July-September 1966 to establish the durability of the M109 using the new super propellant charge.

The vehicle was severly damaged and the crew experienced some discomfort as a result of the XM119 charge blast. Details of the failures encountered during the durability test are given in table 1.

The USAARTYBD concluded that the M109 was not compatible with the super propellant charge XM119 for the following reasons.

1. Excessive maintenance required.

2. Excessive blast pressure is harmful to crew.

3. Potential safety hazard in cracked muzzle brake and bore evacuator.

4. Blast and flash reveal the position.

As a result of failure to meet the M109 extended range requirement with the XM119 charge a working group was formed to determine a suitable course of action. Since ruggedizing the vehicle would not solve the problem it was determined that any successful solution would require a reduction in blast over-pressure.

Two possible alternative proposals were selected:

1. Use F.R.G. muzzle brake on standard M109.

2. Replace existing M126E1 tube with the new long tube being developed for the XM138 programme and use the XM119 charge.

Subsequently, a blast comparison test between the U.S. and F.R.G. muzzle brake was conducted in February 1968. The gauge layout and results obtained are shown in figs. 1a and 1b. The results show that from a blast point of view the F.R.G. brake is somewhat superior to U.S.

A 2100 round, XM119 charge durability test using a standard M109 equipped with the F.R.G. muzzle brake was initiated in January 1968 to determine compatibility of the system. The test was tentatively terminated in February 1968 after 1722 rounds of XM119 charge had been fired and 582 miles of operation has been accumulated. The results of this test are given in table 2.

The long tube proposal for extending the range will now be discussed. Advantages of this approach are that it would:-

1. Achieve 18,000 meter range.

2. Give acceptable blast over-pressure.

3. Give acceptable firing loads.

4. Increase vehicle stability.

5. Use M107 family stockpiled projectiles.

6. Increase cannon life (8,000 rds).

7. Be a "low risk" project.

8. Have considerable potential "range growth".

In a comparison of standard and long tubes, blast over-pressure readings were measured at four locations for both the standard M126E1 (116 inch shot travel) tube and the longer tube XP-8 (200 inch shot travel). Both tubes were equipped with the standard M109 muzzle brake. Three sets of readings were recorded:

M126E1 tube with XM119 charge 8
M126E1 tube with M4A1 charge 7
XP-8 (long tube) XM119 charge 8

Results are shown in fig. 2.

Obviously any solution to the over-pressure problem with charge 8 which results in pressures not greater than the standard charge 7 and the M126E1 tube combination would be satisfactory. This is based on the experience gained from firing thousands of charge 7 rounds from individual M109s. It can be seen from fig. 2 that the blast pressure for charge 8 with the long tube is less than the middle reading pressure which is charge 7 with the M126E1 tube. It is also significantly lower than charge 8 with the M126E1 tube.

Chamber and muzzle presure have been compared under the above firing conditions;

Chamber and Muzzle Pressure Comparison Firing Data

Cannon	Weapon	Charge	Zone	Chamber Press. psi	Muzzle Press. psi
M126E1	M109 SP	M4A1	7	36,400	7,500
M126E1	M109 SP	XM119	8	48,000	13,000
XP-8*	M109 SP	XM119	8	34,600	7,000

*Long Tube

Both chamber and muzzle pressure are lower than when firing charge 8 long tube than charge 7 short tube. Therefore the long tube lower blast pressure readings result not only from the muzzle brake being further from the vehicle but also from the lower muzzle pressure.

Fig. 3 shows the M109 vehicle equipped with the long tube.

Item 7 The interaction of the man-weapon system and studies involving muzzle gas dynamics Mr. S.S. Lentz, U.S.

Limited studies have been conducted at the Ballistic Research Laboratories involving muzzle gas dynamics and its effect on the interaction of the man-weapon system. Equations have been developed including the effects of muzzle brakes and muzzle brake compensators for predicting the dispersion of automatic weapons fired in short bursts from the shoulder of a rifleman in the standing position. The purpose of developing the equations was to determine the contribution of the various weapon parameters in dispersion and to determine methods of reducing their effect. In the equations, the motion of the weapon was considered to be a rigid body rotation about the centre of the buttplate and the length of burst was restricted to periods of time which did not exceed man's reaction time (0.14 to 0.20 sec).

An empirical approach was pursued because of the complexity of the constraints placed on the weapon through the arms and shoulder of the rifleman. The mathematical model considered is illustrated in fig. 1. Constants for the

equations of rotation were determined empirically and include constants of integration combined with correction factors to compensate for the effects of the moment of inertia and physiological response of the arms and shoulder and for errors in the location of the point of rotation. To obtain the constants, target data were analysed from tests previously conducted by the Development and Proof Services, the Human Engineering Laboratory, and Ft. Benning. The following weapons were fired in the tests:

(a) BAR

(b) M14 Rifle

(c) M2 Automatic Carbine

(d) M16 Rifle

(e) Automatic Cal. 0.22 Rifle.

By introducing the values for the weapon parameters and the distance between target impacts in the equations, the constants A_2 and A_3 were determined. The resulting equations are as follows: :

$$\theta_2 = \frac{A_2}{I} \cdot \frac{I_r}{R} \cdot h$$

$$\theta_3 = \frac{A_3}{I} \cdot \frac{I_r}{R} \cdot h$$

where:

θ_2 = distance between the first and second impacts on the target, mils

θ_3 = distance between the first and third impacts on the target, mils

I = moment of inertia of the rifle about an effective pivot at the centre of the buttplate, lb ft sec^2

I_r = recoil impulse, lb sec

R = cyclic rate, shots per minute

It should be noted that the dispersion is directly proportional to the recoil impulse, thus the contribution of a muzzle brake should significantly affect dispersion. If a muzzle brake compensator is considered, the equations for predicting dispersion are modified by adding a clockwise moment term:

a. $\theta_2 = \frac{A_2}{RI} [I\ (h) - I_c\ L]$

b. $\theta_3 = \frac{A_3}{RI} [I\ (h) - I_c\ L]$

where:-

I_c = compensating impulse, lb sec

L = horizontal distance from centre of buttplate to centre of muzzle compensator, in.

As a result of the study of interaction of the man-weapon system, separate investigations were planned to continue the study of the functions I_r, I, R and L with respect to their effect on dispersion. For the purpose of this discussion, we are primarily interested in the reduction of the effect of the gas term in the equation for recoil impulse through the use of muzzle brakes and muzzle brake compensators.

$$I_r = \frac{W_p V_p}{g} + \frac{W_c G}{g}$$

where: I_r = recoil impulse measured with the ballistic pendulum, lb sec

W_p = weight of the projectile, lbs

V_p = velocity of the projectile measured with lumiline screens, ft/sec

g = gravity, ft/sec²

W_c = weight of charge, lbs

G = effective escape velocity of the gas, ft/sec

Study of the available gas term is important in the design of muzzle attachments since the ratio of W_c/W_p varies considerably in military small arms. For example

Rifle	W_c/W_p
M14	0.33
M16	0.50
Experimental Weapon	1.00

To determine the effect of variation in the ratio of W_c/W_p, the single baffle brake shown in fig. 2 was constructed for a Cal. 0.223 rifle. The tubular support extended rearward over the barrel to provide a large expansion chamber. It was anticipated that arrangements for reducing the blast and noise might be later incorporated in the chamber.

A ballistic pendulum was used to measure the recoil impulse with and without the brake. Tests were conducted with three weights of projectiles and several weights of charge, giving a range of weight of charge to weight of projectile from about 0.3 to 2.7. The results are shown in fig. 3.

In an attempt to obtain a simple method of describing the action of a given brake on a given weapon, several efficiencies, η, were calculated from the data. Fig. 4 shows:

η_1 based on recoil energy
η_2 based on recoil momentum
η_3 based on momentum of gas

When considering only the action of the brake, the recoil energy, or η_1, is not considered a pertinent factor because it includes the weight of recoiling parts. The recoil momentum is not especially pertinent because it includes the momentum of the projectile. The momentum of the gas is important in the braking, and it turns out in this case, that the efficiency based on it is practically constant. We can say, therefore, that in this particular combination of brake and rifle, the brake diverts a constant proportion of the gas momentum rearward, irrespective of the magnitude of the gas momentum. Whether or not a similar condition holds for other combinations or calibres is not known. An analysis of other test results may be interesting.

Further studies have been conducted to determine the reduction in recoil impulse as the gases are deflected at a variety of angles to the centreline of the bore with the deflecting baffle placed at different distances forward of the muzzle. In addition, muzzle devices have been investigated in which lateral holes were drilled through the barrel near the muzzle to replace the baffle and the gases were vented into a perforated sleeve surrounding the barrel. The sleeves provide sound attenuation, flash suppression and compensation. The efficiency, η, of the two devices was determined in terms of ability to divert the gas momentum as follows: :

Condition	Type A η	Type B η
Perforated barrel	0.86	0.90
Perforated barrel w/sleeve	0.49	0.83

NOTES:
1. Type A about 1.25 ins of barrel after perforations.
2. Type B about 16 ins of barrel after perforations.
3. Efficiency was lower with the addition of the sleeves which covered perforations and unperforated sections of barrel.

An efficiency statement is helpful in providing a number for each muzzle device which is relatively independent of the loading ratios of ammunition. For example, an efficiency of 1.00 represents the diversion of the total gas momentum 90° to the direction of undisturbed flow and efficiency of 2.00 represents the diversion of the gas momentum 180° to the direction of undisturbed flow.

Muzzle brake compensators have been studied and a number of the devices have been tuned using the ballistic pendulum. To optimize the tuning, the weapon is placed on its side in the pendulum bob and the venting at the muzzle is varied until the resultant vector formed by the recoil impulse and the compensation impulse passes directly through the effective point of rotation in the man. Studies of muzzle brake compensators verify the following.

(a) There is no true universal setting which can be made equally effective man-to-man and position-to-position.

(b) Blast and noise experienced by the firer are generally increased.

(c) Flash in many cases is increased.

SESSION III - PHYSIOLOGICAL ASPECTS

Item 1.1 Instructional Film - "DANGEROUS NOISE" - Ministry of Defence (Naval) Reference A1868. Notes prepared for service and official recipients
Surgeon Commander R.R.A. Coles, R.N., Royal Naval Medical School, Alverstoke, Hampshire, England

This film was proposed by the RN Medical School, accepted and ordered by the Ministry of Defence (Director General Naval Training) and made by Stewart Hardy Films Ltd. under the direction of Mr. G. Fergusson and with Surgeon Commander Coles as technical advisor. The final script was the work of Mr. Fergusson, advised by the Royal Navy and Royal Marine departments concerned, by an invited panel of experts on hearing conversation and by representatives of the Army and Royal Air Force.

Whilst the primary object of the film was to meet the requirements of the Royal Navy, Royal Marines, naval dockyards, etc., care was taken in Parts 1 and 2 by means of suitable illustrations to show that the same problems and remedial measures exist in the Army, in the Royal Air Force and in industry.

The film is in colour, with normal (optical) sound, and is in 16 mm size. It divides into three parts on separate reels:

Part 1, sub-titled "Listen while you can", runs for 21 minutes. This is intended for audiences of persons who are exposed to high levels of noise. It makes them aware of the harmful effects of noise and the means of preventing these effects.

Part 2, sub-titled "Medical aspects and hearing conversation", runs for 22 minutes. This part is more technical than Part 1, but repeats several sequences shown in Part 1. It is intended for medical, administrative and technical audiences. It describes noise deafness and such matters as noise measurement and evaluation, noise reduction, ear protection and monitoring audiometry.

Part 3, sub-titled "Hear your enemy", runs for 11 minutes. It is classified RESTRICTED and is intended primarily for Royal Marines and other ground forces. It is concerned with the harmful effects of previous noise exposure on the ability to detect the sounds made by approaching enemy personnel.

Applications from abroad for loan, issue or purchase of Parts of the film including Part 3 should be made through official channels to the Director General of Naval Training, Ministry of Defence (Navy), London, S.W.1. Alternatively, Part 1 (ref. No. U.K. 1888) or 2 (ref. No. 1889) may be hired or purchased (i), in the case of applicants from abroad, from the Films Division, Room 507, Central Office of Information, Hercules Road, London, S.E.1. or (ii), in the case of applicants from within the United Kingdom, from the Central Film Library, Government Building, Bromyard Avenue, London, W.3 (the hire fee in this case being £1 per part for the first day of use and the purchase charge being £54 per part).

Item 1.2 Communication problems with intermittent impulse noises
Surgeon Commander R.R.A. Coles, RN - U.K. (Paper not actually presented)

The speech-to-noise ratios at the moments of gunfire noise are so low that speech at those moments is inaudible, with or without ear protection. Between the noises, in periods of complete or relative quiet, the audibility of speech depends mainly on the sound level reaching the listener. In many situations, for example in field-firing exercises, the listeners are at considerable distances from the speaker and the audibility of verbal communication, such as fire-control orders, may be marginal even without ear protection.

These potentially dangerous situations present the greatest single obstacle to use of ear protection and preservation of the good hearing ability that is necessary for soldiers' maximum efficiency. The twin problems of need for ear protection, and unimpaired communication must be considered together and research effort made to provide a satisfactory solution to these problems.

Table 1 gives, on the left hand half, the peak levels of impulse noises that are potentially hazardous for lung damage, eardrum rupture and auditory damage. In the right half of the slide are listed the peak levels produced by some military weapons and other impulse-noise sources.

Situations where the need for ear protection together with a need for good hearing ability arise very frequently in military operations. For example a section laying down covering fire, especially when lying "en-echelon", need to protect their ears; at the same time, there is a clear need for inimpaired audibility of fire-control orders. The safety of the adjacent sections that are possibly making a flanking attack depends on prompt and correct responses to the fire control-orders.

The standard British issue, V.51R-type, earplug reduces speech sounds by about 20 decibels. The Selectone-K earplug, by selecting the high tones for greater attenuation and the low tones for less attenuation, is better but still produces 15 decibels reduction of speech sounds. Thus, use of plugs having the property of "frequency-selectivity" offer some advantage, but not enough to constitute a major improvement in the communication problem.

The performance of various earplugs has been studied in an "artificial ear". A central narrow tube corresponds to the ear canal, and the trial earplugs are inserted in the left end of it. A 1-inch Bruel and Kjaer microphone at the right measures the sound level reaching the "tympanic membrane" and a $\frac{1}{2}$-inch microphone at the left measures the sound level outside the ear canal. A hearing-aid type of telephone on top of the "ear" is used to produce the sound field outside the ear canal. The difference in levels recorded by the $\frac{1}{2}$-inch microphone on the left, and the 1-inch microphone on the right is a measure of the attenuation properties of the earplug in the "ear canal".

Very useful developments have been made by Mr. M.R. Forrest, of the Royal Naval Medical School, who has produced experimental earplugs with only about 5 decibels attenuation of low intensity sounds, such as speech, but with rising attenuation as incident sound intensity rises. At the most hazardous level they provide virtually the same degree of protection as the standard V51R earplug, which has a virtually constant 20 decibels attenuation at all intensity levels.

Another "amplitude sensitive" device has been produced by the Explosives Research and Development Establishment Waltham Abbey Essex and is known as the ERDEfender.

It consists of a bulky pair of ear-muffs each with a microphone on the outside, an internal amplifier with peak limiting characteristics, and a telephone earpiece inside. Up to a level of 95 decibels, all sounds are transmitted with a 1-to-1 gain function. Speech intelligibility with the ERDEfender is under study at RN Medical School and appears to be very good; also, because there is a microphone-amplifier-speaker unit for each ear, localisation of sound sources and associated phenomena are unimpaired (and possibly enhanced due to the wider spacing of the microphone as compared with the ears). The gain of the amplifier is limited to 95 decibels, and sounds of 95 to 135 decibels are transmitted at the 95 decibel level; above 135 decibels however some of the additional external sound enters the ear, having passed through or around the body of the ear-muff. At low levels therefore speech is heard without impairment, whilst at high levels the headset behaves like an ordinary pair of ear-muffs. Its likely applications are for heavy weapon and artillery firings, though some further development is needed to make it sufficiently robust for use in the field.

In summary the ERDEfender is proably too bulky and expensive for use by infantrymen, but in this case "amplitude-sensitive"earplugs will probably provide sufficient attenuation of most of the noise hazards to which these men are exposed. For the higher noise levels produced by heavy weapons the extra attenuation provided by the ERDEfender is valuable and the headset is more suitable for the smaller numbers of relatively static personnel exposed in this situation. In either case, communication is likely to be very much better than with existing forms of ear protection.

Item 1.3 Auditory damage risk from impulse noise Surgeon Commander R.R.A. Coles, RN

Introduction

The majority of work on auditory damage has been with steady-state types of noise. In fact, as outlined in a recent review of the subject (Acton, 1967), there are over 30 published damage risk criteria (D.R.C.) of varying complexity which express the levels of a steady-state noise constituting an acceptable degree of auditory hazard. Many of these criteria may be adjusted for exposure duration from 8 hr down to 2 min, for quiet intervals between exposures, for recurrent short burts of noise (down to 0.5-sec bursts), and for pure-tone or narrow-band elements in the noise. For impulsive elements in the noise, little advice is given other than a vague warning of probable additional hazard.

The pioneer work of Murray and Reid (1946), based on gun blast and temporary hearing loss studies in Australia during World War II, enabled them to rank-order a number of named weapons in terms of the peak pressures produced and the need for ear protection. Next, in 1965, three independent sets of rather tentative conclusions regarding gunfire noise and auditory hazard were published in the form of U.S. Army Human Engineering Laboratories standard S-1-63B and as open publications by Pfander in West Germany and by Rice and Coles in the United Kingdom. More recently, the latter authors, in association with the U.S. Army workers, have published a more elaborate criterion for measurement and evaluation of auditory damage risk from impulse noises (Coles, Garinther, Hodge and Rice, 1968). This paper will now be summarised.

Impulse noise measurement

An essential pre-requisite of any standard for limiting noise exposure is a method of measuring and expressing the physical characteristics of the noise. The meter ballistics of conventional sound level meters are not suitable for measuring high-intensity short-duration impulses, whilst impact noise analysers have intensity/duration integration properties which do not as yet appear to be a reliable expression of the true characteristics of the noise (Rice and Coles, 1965). At the present time, therefore, measurement is best obtained by oscillographic display and subsequent analysis of the impulse waveforms. For this purpose, the most suitable equipment at present is considered to be the Bruel and Kjaer type 4136 $\frac{1}{4}$-inch or type 4138 $\frac{1}{8}$-inch condenser microphone with its protection grid removed (Forrest, 1967) and orientated at grazing incidence to the wave front. A Tektronix type 564 dual-trace storage oscilloscope provides a very useful means of recording the waveform.

Using this kind of measuring equipment, the detailed requirements of which are discussed in the author's original paper (Coles et al., 1968), the display may be evaluated in terms of peak level, principal pressure wave duration (A-duration) in the case of simple waveforms, and pressure wave envelope duration (B-duration) in the case of complex waveforms, echoes and reverberant sound fields, as shown in fig. 1. Rise time is also illustrated but it is not considered to be a parameter of major importance for impulses of explosive origin in which the rise time is virtually

instantaneous but is limited in effect by the inability of the ear drum and middle ear to respond to such rapid acoustic events in a linear fashion. Where the rise time is greater, as in most industrial and many laboratory noises, the ear may transmit the physical properties of the noise more faithfully however, and for a given peak level this type of noise appears to be more hazardous than the explosive type of noise (Cohen, Kylin and LaBenz, 1966). On the other hand, when rise times are in excess of about 0.5 msec the auditory hazard appears to be reduced.

Assessment of auditory hazard

This was based on studies of threshold shift, in most cases of temporary nature, following exposures to gun, small-arms and other explosive noises of known physical characteristics. The evidence is supported by theoretical and laboratory studies of the effects of peak level, rise time and pulse duration of the sensation of loudness. The results of both threshold shift and loudness studies are summarised in appendices to U.S. Army Human Engineering Laboratories technical memorandum 13-67, but an outline of the manner in which the data were used is given below.

1. Amount of auditory effect allowable

As a secondary criterion for evaluation of experimental data, the body of experts comprising the U.S. National Academy of Science's Committee on Hearing, Bio-acoustics and Bio-mechanics, Working Group 46 considered (CHABA, 1965) that temporary threshold shifts measured 2 minutes after the end of noise exposure (TTS_2) were acceptable if within the following limits in 50 per cent of persons exposed:

10 dB at or below 1000 Hz,
15 dB at 2000 Hz,
20 dB at or above 3000 Hz.

For steady-state noise, such TTS_2 is believed to be equivalent approximately to the likelihood of eventual PTS (Permanent threshold shift) from recurrent exposures to the same noise: in practice, however, the PTS may be considerably less than the indicated by the end-of-day TTS_2 (Ward, 1966). Whilst impulse noise differs somewhat from steady-state noise in respect of its auditory effects, e.g., nearer to a linear relationship to amount of exposure and a wider scatter of threshold shifts (Ward, Selters and Glorig, 1961, and others), the authors considered it appropriate to adopt the CHABA limits of threshold shift measured two minutes after the last of a series of impulses, but with the qualification that they should be applied to 75 per cent of persons exposed. Also, in view of the possibility that the time course of TTS to PTS may be considerably shorter in the case of impulse noise, the exposure limits should be regarded as covering many fewer, perhaps 10, exposure occasions per year. Indeed the variation in effective exposure to impulse noise, due to diffraction effects from variations in orientation of the ear and the tendency to highly directional characteristics in the noise and possible "mach-stem" types of summation of direct wavefronts and wavefronts reflected off the ground or other objects, make it unwise to relax ear protective measures even for single occasions of exposure.

2. Relation of noise characteristics to auditory effect

Using the CHABA threshold shift limits, all the experimental data available were corrected to TTS_2 (after Kryter, 1963) and plotted on a graph having peak pressure level as the ordinate (corrected by 5 dB for greater auditory hazard where impulses arrive at the ear at normal incidence) and impulse duration as the abscissa. The parameters noted against each data plot were number of impulses, percentage of persons exceeding the CHABA limits, the type of threshold shift (TTS or PTS) and the type of duration (A or B). From these, and taking into account the general shape of the intensity v. duration curve in respect of loudness of impulse, a damage risk criterion or exposure specification was derived.

The specification derived by the method outlined above is shown in fig. 2.

Apart from the warning given above in paragraph (1) concerning variations of effective noise exposure in practice, there are a number of other limitations and adjustments to the criterion which need clear statement with the criterion.

(i) Where impulses arrive at normal incidence to the ear, a correction of 5 dB should be made to the peak level to allow for the greater auditory hazard involved.

(ii) The criterion is based on repetition rates in the order of 6-30 impulses/min, the repetition rates with greatest hazard (Ward, 1962), and exposures to around 100 impulses per occasion on perhaps 10 occasions per year. When greater or lesser rates are used, it is difficult to quantify the reduced hazard and it might be advisable to ignore this factor and thereby retain an inherent safety factor. Where exposure is to occasional single impulses only, an estimate of 10 dB has been made for the reduced hazard and the higher peak level allowable therefore. Where other amounts of exposure occur, interpolation and extrapolation may be considered. Forrest (1967) has considered this matter in further detail and estimates that duration x number of exposures (for up to 100 exposures) might be a more suitable measure of hazard.

(iii) If it is desired to cover a larger percentage of persons, the specified peak levels might be lowered by about 5 dB, 10 dB or even 15 dB to cover the 90, 95 or higher percentiles respectively. It is pointed out, however, that average threshold shifts of the CHABA limits magnitude already involve a considerable safety margin with respect to the threshold of auditory disability: it is considered, therefore, that the 75 percentile would be suitable for most practical purposes.

(iv) When ear protectors are worn, allowances of about 20 dB for earplugs (e.g., V-51 R type or "glass-down") or 35 dB for fluid-seal ear-muffs may be applied.

Acknowledgements

The authors wish to record their appreciation of the contribution of their colleagues, G.R. GARINTHER and D.C. HODGE, in preparation of the damage risk criterion described in this paper and of the support of the Medical Research Council.

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Item 2 Noise damage risk criteria Lt. Col. J.L. Fletcher, U.S.

The sound pressure levels (SPL's) from conventional artillery are known to be of sufficient intensity to be a hazard to the hearing of crew members. Artillery provided with muzzle brakes constitute an even greater danger in view of the increased SPL resulting from blast deflection into crew positions. To date, no adequate helmet or other hearing protective measure is routinely provided for artillery crew members. In view of this situation, it would appear that the hearing of crew members is in danger and that appropriate measures should be taken to conserve hearing. A start in that direction is the formulation of damage risk criteria (DRC) for exposure to impulse sound. Although reasonably adequate damage risk criteria are available for exposure to steady-state noise, no widely accepted criteria exist for impulse noise.

In the U.S., the National Research Council - National Academy of Sciences, Commission on Hearing Bio-Acoustics and Bio-Mechanics (CHABA) has been concerned with this problem. Recently, Dr. W.D. Ward formulated tentative impulse noise DRC and circulated them among WG 50 CHABA members. These criteria were based in large measure on results of work of one of the participants of this meeting, Surg. Cdr. R.R.A. Coles, RN. The following is extracted from Dr. Ward.

In 1965 Rice and Coles (5th ICA, Liege) presented an article on "Impulsive noise studies and temporary threshold shift". On the basis of some studies of temporary threshold shifts (TTS) produced by various weapons, they recommended a limit of 165 dB SPL for "occasional single impulses" provided that the root mean square (RMS) level dropped by 20 dB in 20 msec or less (i.e. under open-field conditions), 155 dB SPL for "repeated exposure". If, as under reverberant conditions the level does not drop 20 dB in 20 msec, the recommended limits are reduced 10 dB i.e., to 155 dB for single pulses, 145 for repeated. They took care of the most sensitive ears by saying that "for persons who are highly susceptible to noise-induced hearing loss, reduction of at least 5 dB should be made on the above values". This, of course brings them back to our 140 dB for repeated pulses, but only under reverberant conditions.

The following year, Gjaevens (Journ. Acoust. Soc. Amer. - JASA 39, 403) reported measurements on various firecrackers and children's toys. Accepting Rice and Coles' 165 dB limit but reducing it by 5 dB to provide for susceptible ears, he found that this 160-dB level was exceeded if ordinary ("Camel") firecrackers went off closer than 1 meter away. Hodge and McCommons (JASA 40, 911) quickly argued that

the 160-dB criterion was too high, because we should try to protect children from any amount of TTS, and it had been shown that 140-dB pulses could produce TTS. Gjaevenes' (JASA 42, 268) report was that protecting children from any TTS would be "difficult in practice" (I am confident he meant "impossible"") and he further argued convincingly that if 140 dB represented a serious risk of permanent loss, the incidence of such losses in Oslo children would be much higher than actually found. But he closes this letter by retreating to 155 dB as a reasonable criterion.

This apparently convinced at least Hodge, if not McCommons, because in 1968, Coles, Garinther, Hodge and Rice collaborated on a joint paper presenting extensive data relevant to impulse DRC that had been gathered at Aberdeen and at Southampton. On the basis of this and other evidence, and using various extrapolative techniques to bring them all together, they offer a new and fairly involved criterion. Two durations are defined: the 'A' duration is the duration of the initial pulse - i.e. from the beginning of the wave front to the first time the pressure passes through normal; the 'B' duration, on the other hand, is the time from onset until the <u>envelope</u> of the pressure fluctuations drops 20 dB below the initial peak pressure level. Their proposed limit for 'A' duration of 1 msec or more is 162 dB, increasing as duration decreases to about 172 dB for 100 microsec, and then accelerating to go off their graph at 177 dB and 50 microsec. The allowable 'B' duration decreases at about 2 dB/doubling-time, from 160 dB at 2.5 msec to 145 dB at about 700 msec. Note that rise time <u>per sec</u> is ignored, probably justifiably.

These limits, they believe, represent criteria that will just produce the CHABA criteria of TTS (TTS_2* = 20 dB at 3 KHz or above) in the most susceptible grazing incidence. For normal incidence, the A criteria should be lowered 5 dB. They indicate that an additional 10 dB decrease would protect all but "an occasional person". Finally, they feel that if only a single isolated pulse is involved, the criteria might be 10 dB higher (as in 1965).

Apparently the curves do no great violence to the data, and they did include all the published information (but of course some of their extrapolation techniques may need future revision, as they indicate themselves). One possible exception is the rapid acceleration of the curve at extremely short durations. This is apparently based on the Fort Knox work with the Benson arc discharge apparatus but in this case the extrapolation appears to me to be so extreme that I would suggest that for simplicity the curve be kept straight, at the same 2 dB/doubling-time that apparently holds for 'B' duration.

So once again we return to the perennial question: "What fraction of ears are to be protected?" If we will settle for 75%, then their suggestion appears to be essentially correct. Let me illustrate this with my particular impulses (square pulse to Altec 20801, giving a damped exponential with B approximately 4 msec, according to Coles et al). According to their chart, the permitted level for B=4 msec is 158 dB, or, corrected to normal incidence (which I use), 153 dB. Now as a matter of fact, when 20 clicks were presented in 1 min at 153 dB to 49 listeners, the 75%ile shift was just about 20 dB at 30 sec recovery. Such a shift would probably drop to about 10 dB in another 90 sec (i.e., TTS_2). 100 clicks might therefore be expected to result in some 50 dB of TTS_2, which is not too badly off.

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*TTS_2 = Temporary threshold shift 2 mins after exposure

The trouble is that the sensitive 25% would have some terrific losses indeed when exposed to 100 of these 153-dB pulses, if extrapolation is warranted (and I think I showed on my ear that it is - JASA 33, 791). The most sensitive ear of the 98 showed a TTS_2 of 50 dB after 20 pulses at 150 dB; 100 pulses would then develop some 250 dB of TTS_2, if the rule held that the TTS is proportional to number of clicks presented! So we must invoke the 10-dB safety factor; this would reduce the limit to 143 instead of 153. Returning to the data, I find that after 20 clicks at 145 dB, the highest $TTS_{30''}$ was 9 dB, which would correspond to a TTS of less than 5 dB. So even 100 pulses would have just reached the criterion for this most sensitive ear in this particular sample.

In my opinion, therefore, we might well recommend a criterion for the armed forces similar to that of Coles et al for a 100-pulse exposure, with a 5-dB difference for normal vs. grazing incidence. What is to be done about situations involving numbers other than 100 is, however, still a moot point, it appears to me. Coles et al said the criterion applied to "50-200" pulses rather than 100. But 200 pulses will produce 4 times as much TTS as 50 pulses in those ears that (1) are affected at all by that level, but (2) get only 5-15 dB of TTS from 50 pulses. So we must be careful to talk about the number of pulses.

Item 3 The effects of gun blast on hearing Dr. M.A. Elwood, U.K.

The U.K. Army Personnel Research Establishment, (A.P.R.E.) has studied the effects of gunfire upon hearing in the British Army which, it is understood, is subjected to the same problems as in other European countries and the U.S.A.

A brief survey of the literature was sufficient to show that the majority of weapons in service were a hazard to hearing. Therefore no attempt was made to monitor the effects of more than a few selected weapons upon the unprotected human ear, and then only in strictly controlled experiments. The adequacy of the issued ear plug was assessed by monitoring hearing ability before and after the wearers had fired their weapons. Sensitivity was assessed to ensure that the relatively small groups of men studied for each weapon included at least some of the more sensitive members of the population. This was done by exposing each man without ear protection to a progressively increasing number of rounds from a rifle. When hearing had been degraded temporarily by 20 dB or more at 3,4,6 and 8 k Hz in either ear men were withdrawn. About one quarter were sensitive to 20 rounds, another quarter to either 60 or 120 rounds, and the remaining half were regarded as relatively insensitive and given no further exposure.

For normal amounts of firing used in training the 'Sonex' ear plug gave adequate protection for most weapons:-

Infantry	7.62 mm	SLR	120 rounds - 35 mins.
	84 mm	Carl Gustav	5 rounds - 2 mins.
	120 mm	Wombat	10 rounds - 15 mins.
	81 mm	Mortar	36 rounds - 3 mins.
Artillery	105 mm	Pack Howitzer	16 rounds - 75 mins.
	25 pdr	Charge 2	150 rounds - 5 hours
	5.5 inch	Charge 2	50 rounds - 5 hours

AFV	105 mm Centurion	200 rounds - 6 hours
	76 mm Salladin	40 rounds - 2 hours

The instructor's position for the SLR has been validated, but more work needs to be done for other weapons.

Unless hearing has already suffered serious deterioration, the wearing of Sonex ear plugs is unlikely to prevent the hearing of normal orders, but whispered or low voice instructions will be missed or distorted. The provision of the muff type of defender (as the RAF Mark 3) can affect to a greater degree, the intelligibility of speech under conditions appropriate to training ranges. The provision of ear-muffs with communication systems would circumvent this problem. The battery operated and peak limited transmission system developed by E.R.D.E., Ministry of Technology, may be suitable for this purpose, but needs further evaluation before adoption for very intense pulses.

The acoustic trauma found in soldiers may arise either from isolated incidents of over exposure, or from cumulative exposures building up to a serious situation. When a soldier is found to have acoustic trauma there is, apart from his own statement, no real means of determining the precise cause of his affliction. Such information could only be obtained by the regular monitoring of hearing abilities with audiograms taken, say, once every month on a random sample of instructors initially and eventually all soldiers, and with experimental study of suspect circumstances. It is as important to avoid condemning, as a result of accident or negligence not readily admitted, weapons, which may be acceptable under appropriate circumstances, as to ensure safety for the user. It may be appropriate to place the safety limitations, as far as they are known, together on a single chart for lung injury, ear drum rupture and inner ear deafness.

An attempt has been made to combine all available information on injury to man due to blast in a single chart. This is given as fig. 1 which shows lethality, lung damage, ear drum rupture and inner ear deafness criteria for various overpressures and pulse durations.

Gun Blast and Muzzle Brake Symposium
List of Participants

Those attending the Symposium included:-

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OTL Siebler
Dr. Ing. Kratz
ORR Bongartz
Dipl. Ing. Grubert
Herr Hornfeck
Dr. Ing Zenner
Herr Wiedeck
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	:	Explosives Research and Development Establishment Ministry of Technology Waltham Abbey Essex.
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Gun Blast and Muzzle Brake Symposium Programme

Introductory

	Opening address. Administrative remarks.	Mr. W.H. Coulthard DD1/R.A.R.D.E.
	Chairman's Introduction.	Mr. F.H. Seeley PS/B R.A.R.D.E. - U.K.

Session I — Measurement and Research

1.	Introduction to measurement.	Mr. G.R. Nice B2/R.A.R.D.E. - U.K.
	1.1 Foil-rupture blast pressure gauges.	Mr. A.W. Bicker F1/R.A.R.D.E. - U.K.
	1.2 Piezo-electric measurement of gun blast pressures.	Mr. K.E.B. Green B2/R.A.R.D.E. - U.K.
	1.3 Noise measurement.	
2.	Recoil measuring equipment at Meppen.	Herr Hornfeck - F.R.G.
3.	Muzzle brake model studies.	Mr. F. Smith D4/R.A.R.D.E. - U.K.
4.	Experimental full calibre firings.	Mr. G.R. Nice B2/R.A.R.D.E. - U.K.

Session II — Development

1.	Experimental designs for muzzle brakes.	Mr. P.B. Shilstone B1/R.A.R.D.E. - U.K.
2.	Recoil velocity measurement.	Dipl. Ing. Grubert - F.R.G.
3.	Test techniques for gun blast testing M109 and 105 mm Howitzer full calibre studies.	Mr. D. Tag - U.S.
4.	Empirical studies on the reduction of muzzle brake blast.	Mr. M.J. Salsbury - U.S.
5.	Muzzle brake design and the reduction of gun blast.	Dr. Ing. Kratz - F.R.G.

6.	M109 Test firings with U.S. and F.R.G. muzzle brakes and XM119 charges.	Mr. R.M. Walsh - U.S.
7.	Interaction of the man-weapon system and studies involving muzzle gas dynamics.	Mr. S.S. Lentz - U.S.

Session III — Physiological Aspects

1.	Introduction to the concept of noise deafness.	Surg. Cdr. R.R.A. Coles RN - U.K.
	1.1 Ministry of Defence (Naval) Film "Dangerous Noise".	
	1.2 Communication problems with intermittent impulse noises - (not presented because of pressure of time).	
	1.3 Auditory damage risk from impulse noise.	
2.	Noise damage risk criteria.	Lt. Col. J.L. Fletcher - U.S.
3.	Effects of gun blast on hearing.	Dr. M.A. Elwood - U.K.
4.	Closing remarks.	Mr. F.H. Seeley PS/B R.A.R.D.E. - U.K.

Note

Discussion followed each paper or group of allied papers and there was a general discussion period at the end of each session.

Session I
Item 1.1 Foil-Rupture Blast Pressure Gauges

List of Figures

FIG. 1

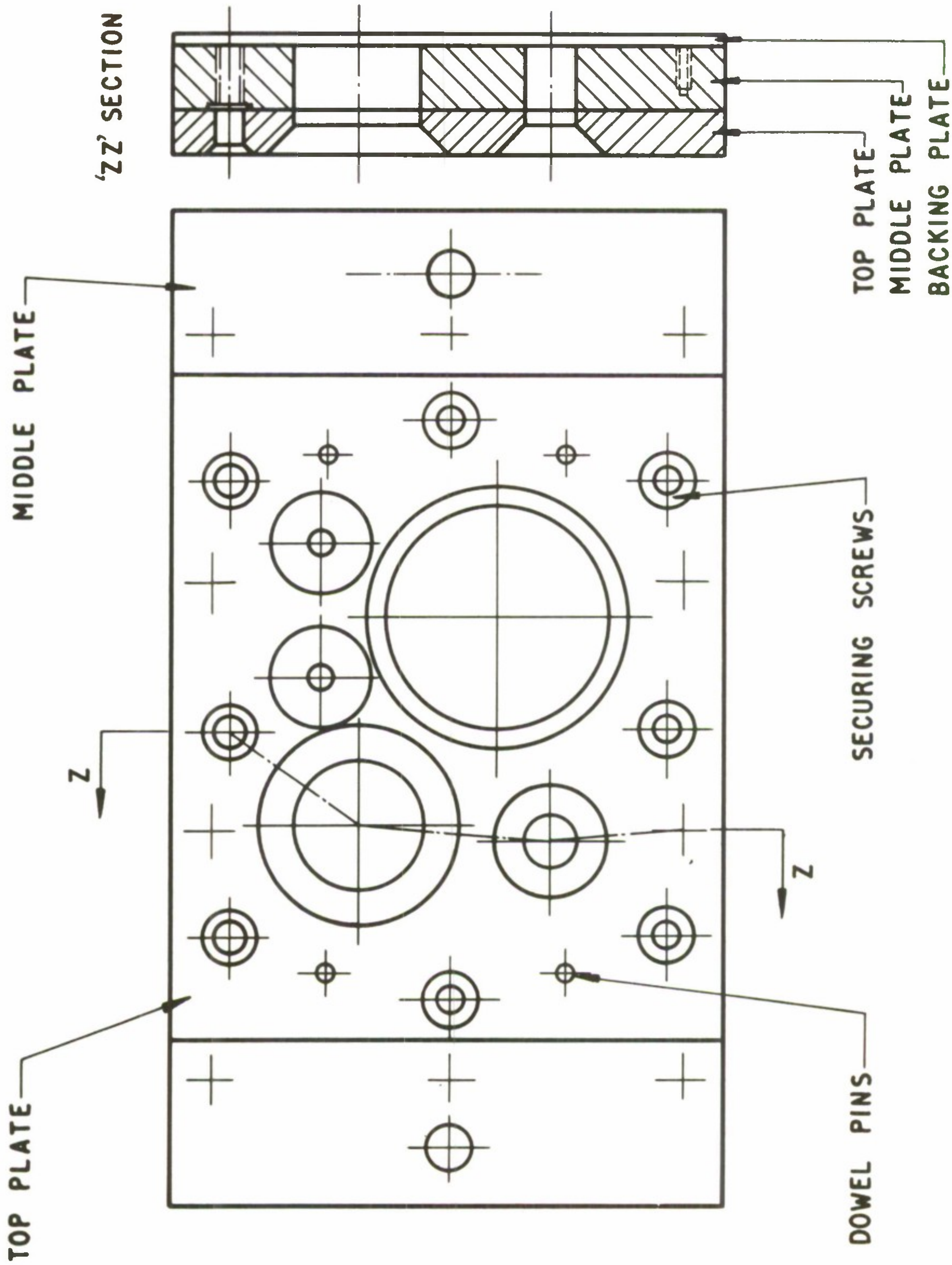

FIG. I DETAILS OF GAUGE CONSTRUCTION

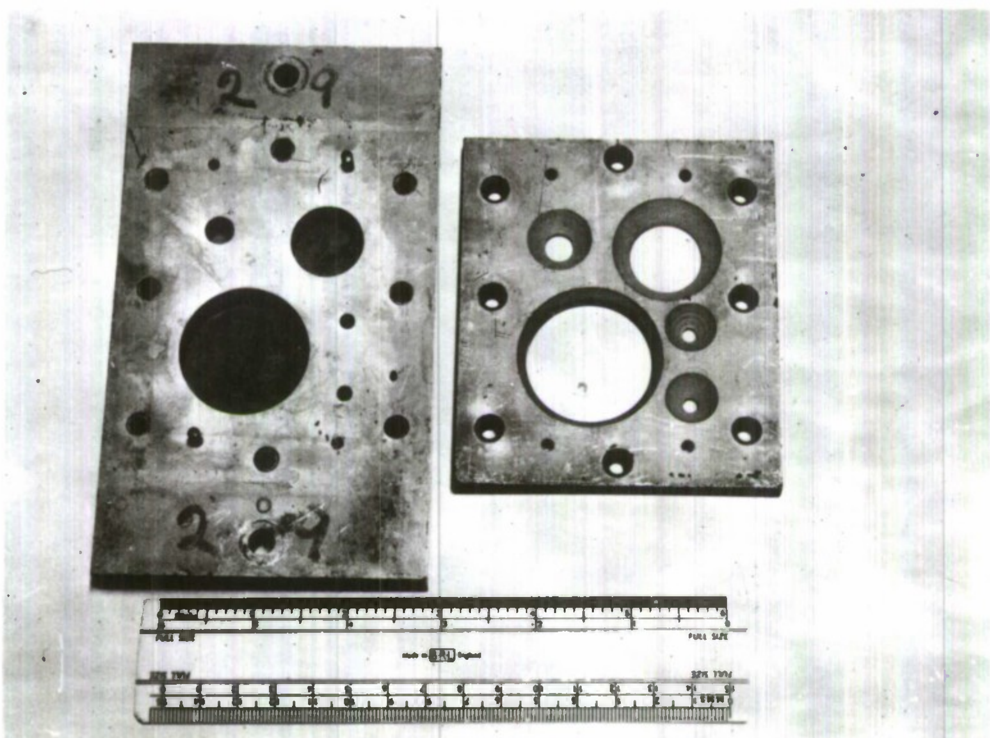

FIG. 2 EXPLODED VIEW OF GAUGE

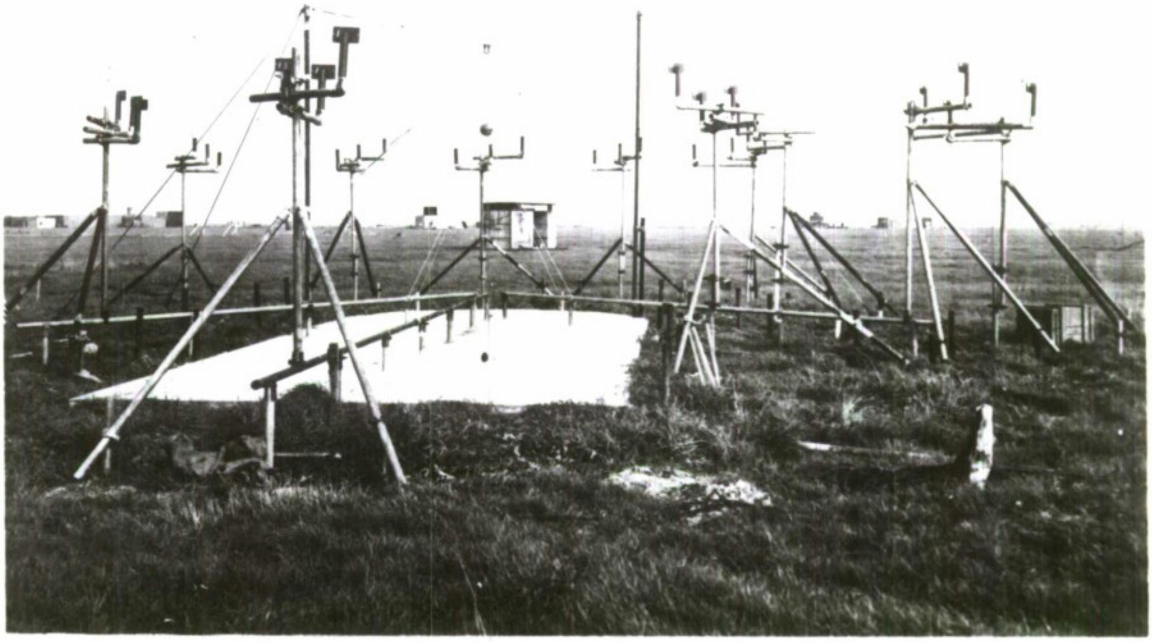

FIG. 3 LAYOUT OF SITE FOR CALIBRATION OF GAUGES USING 8 lb H.E. CHARGE

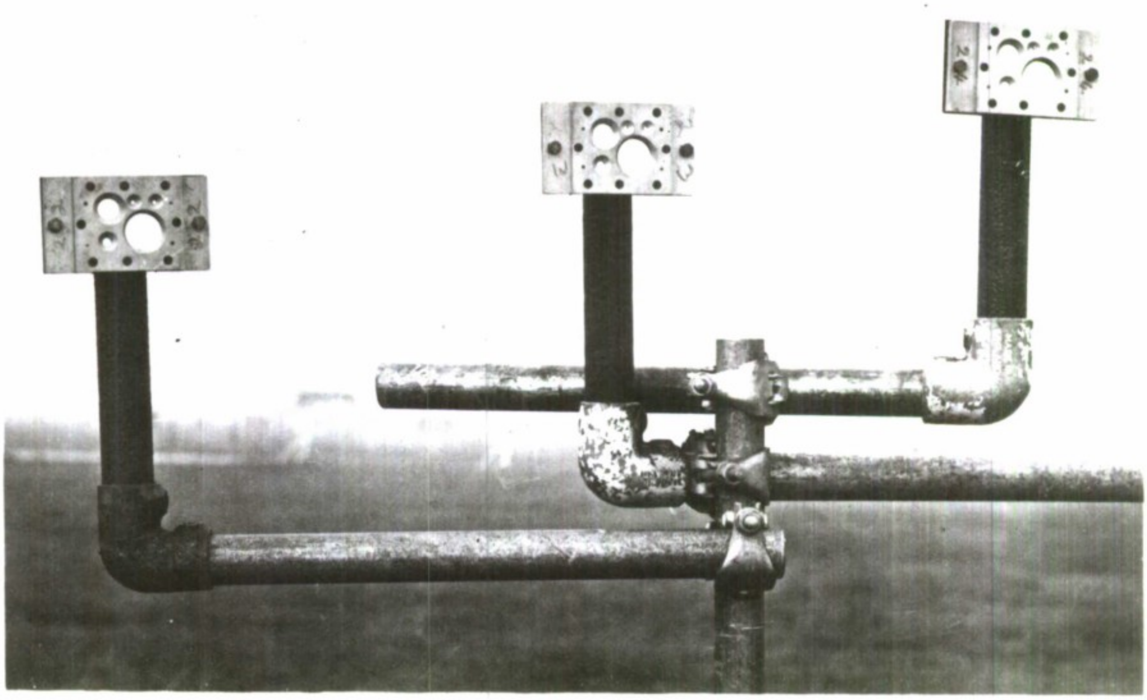

FIG. 4 SET OF THREE GAUGES AT SLIGHTLY DIFFERENT RADIAL DISTANCES AT EACH STATION

FIG. 5

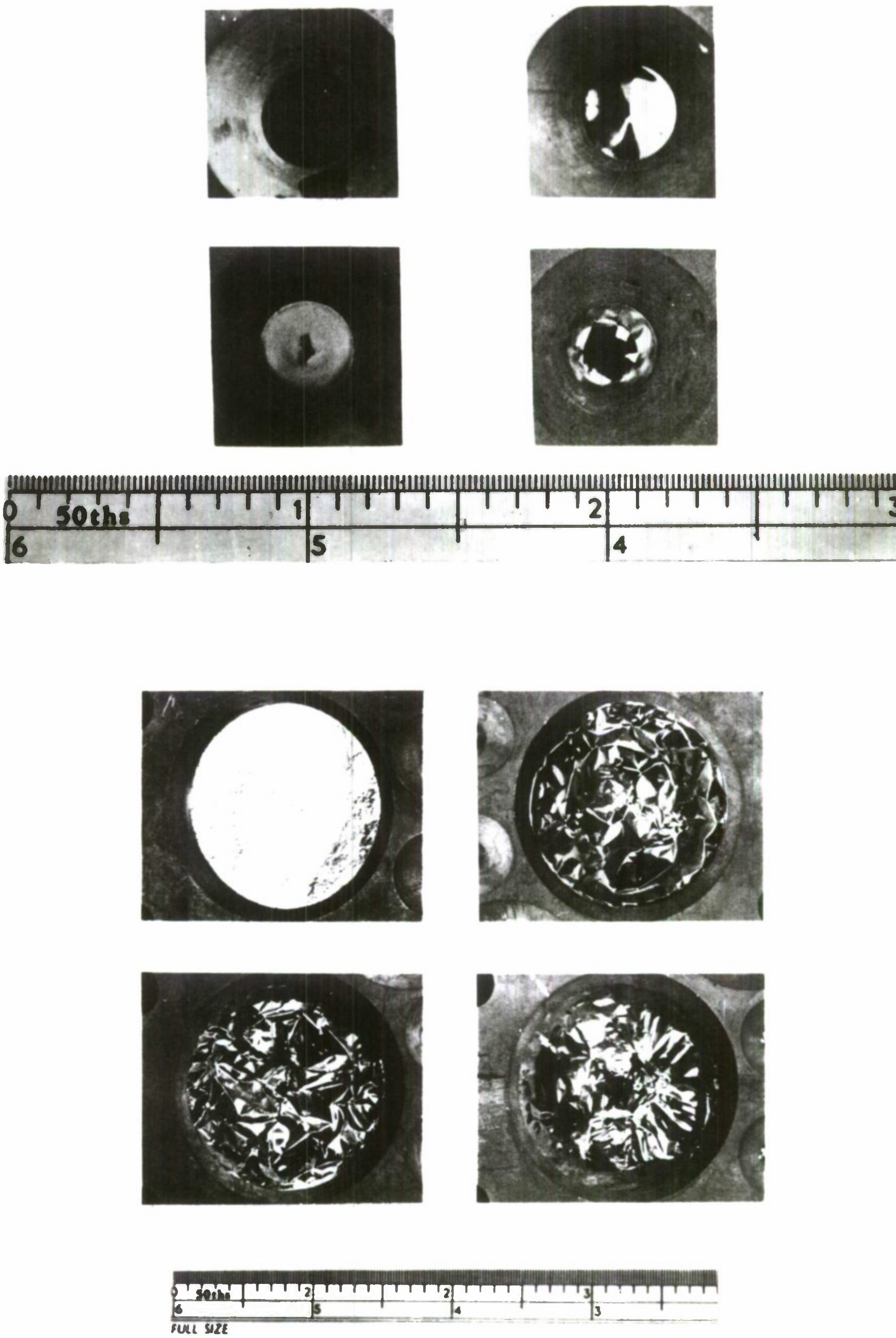

FIG. 5 SUCCESSIVE STAGES IN RUPTURE OF DIAPHRAGMS

FIG.6

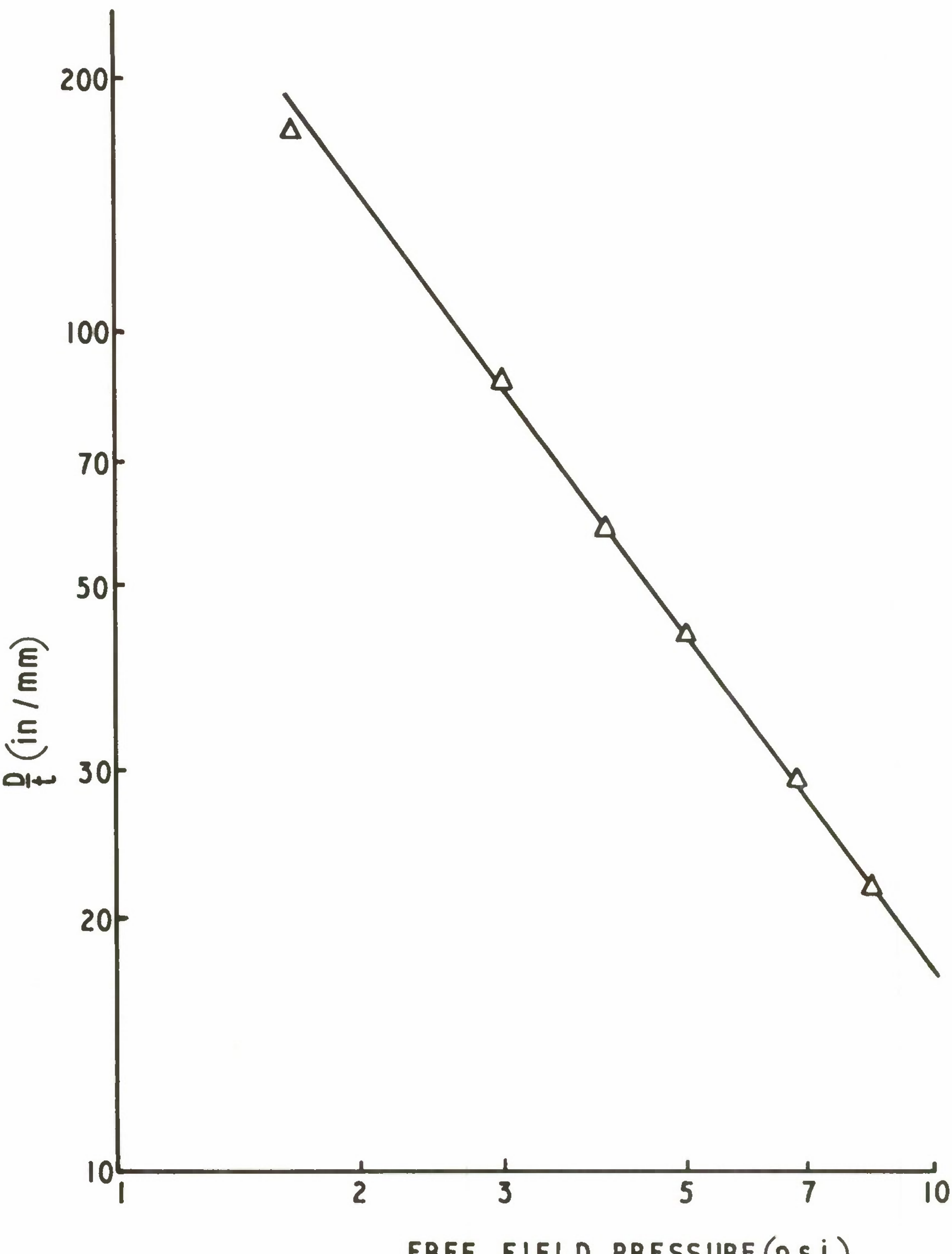

FIG. 6 CALIBRATION OF 1·4 in DIAMETER APERTURE USING 0·008 mm FOIL

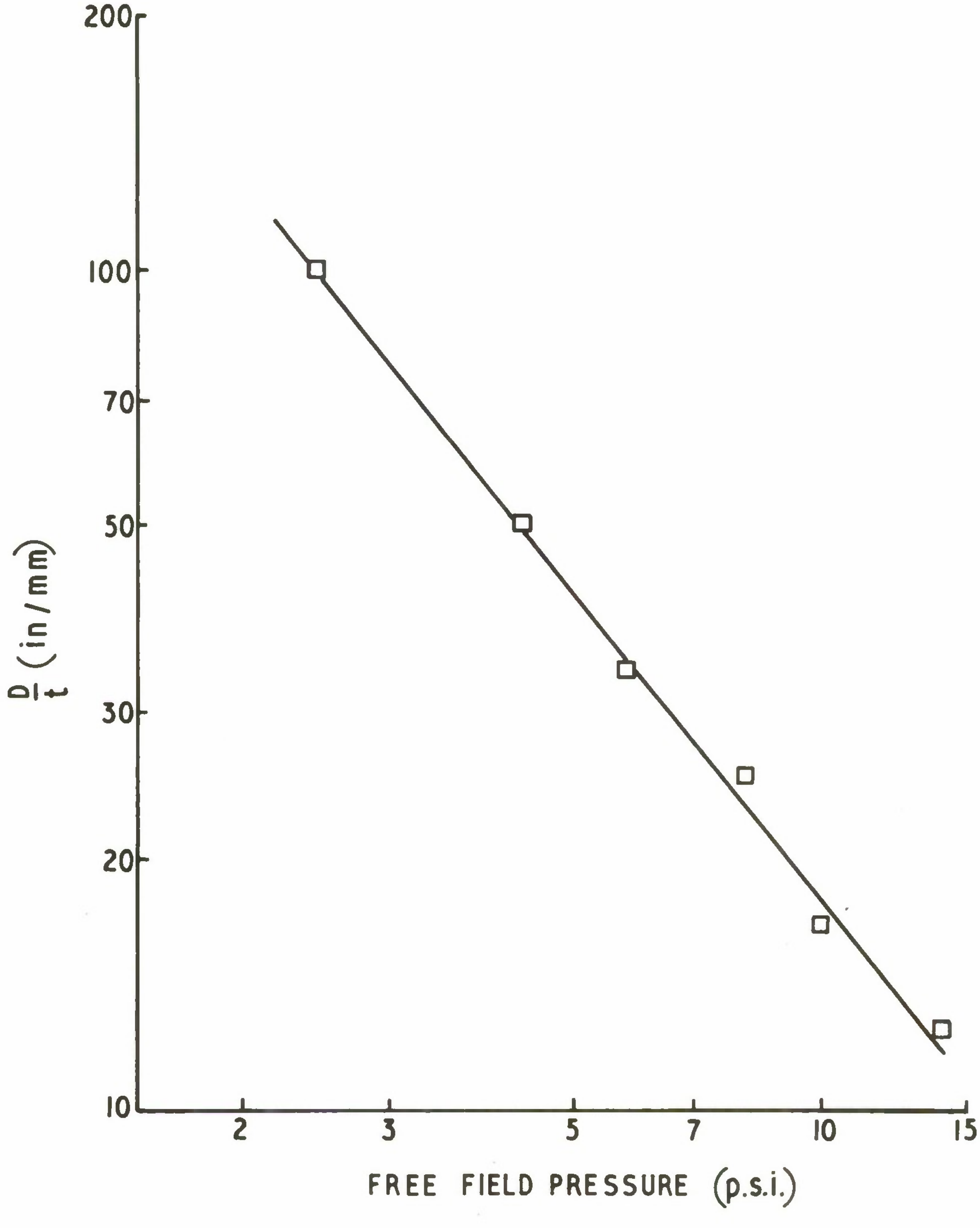

FIG.7 CALIBRATION OF 0·8 in DIAMETER APERTURE USING 0·008 mm FOIL

FIG. 8

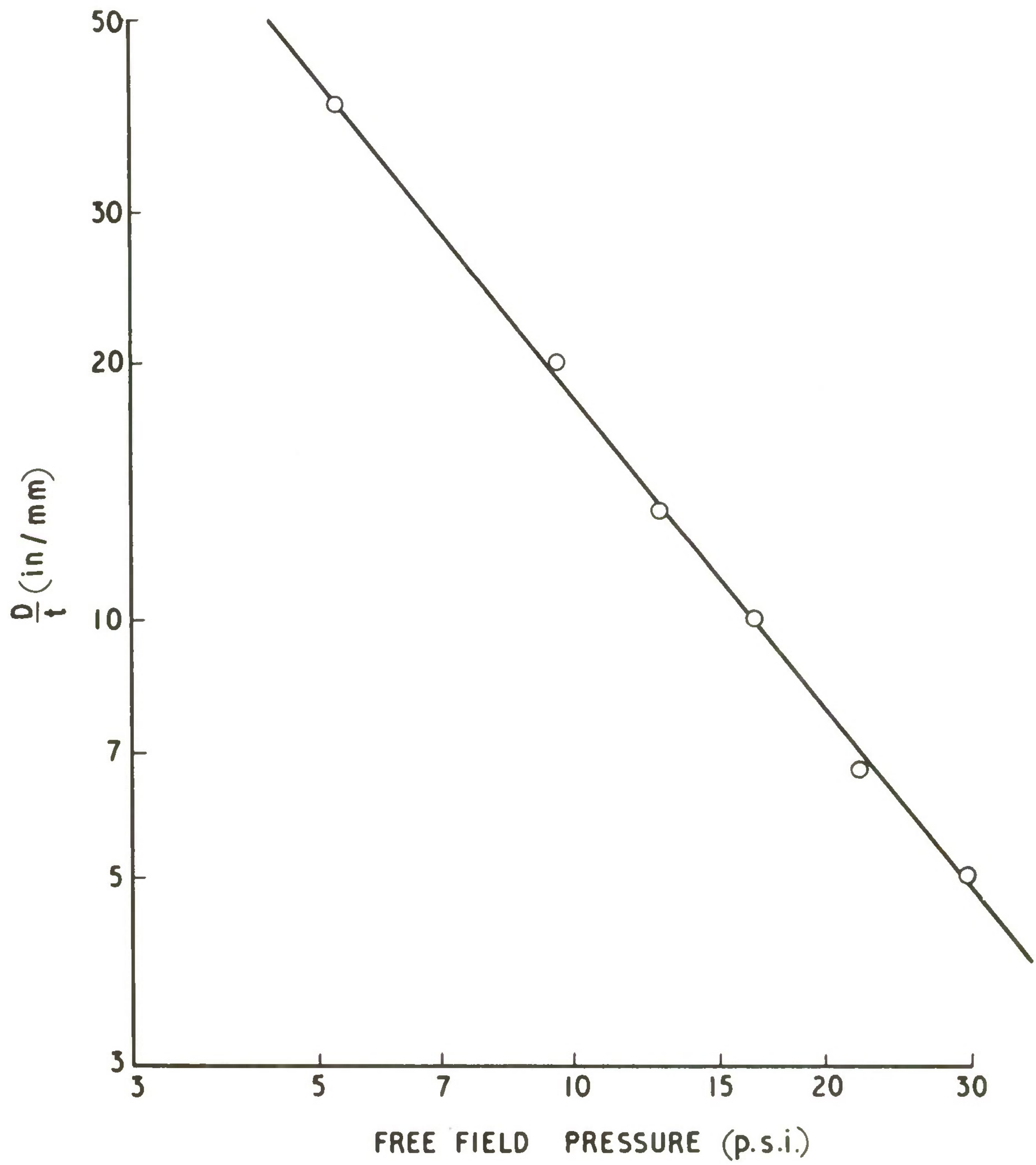

FIG. 8 CALIBRATION OF 0·32 in DIAMETER APERTURE USING 0·008 mm FOIL

FIG. 9

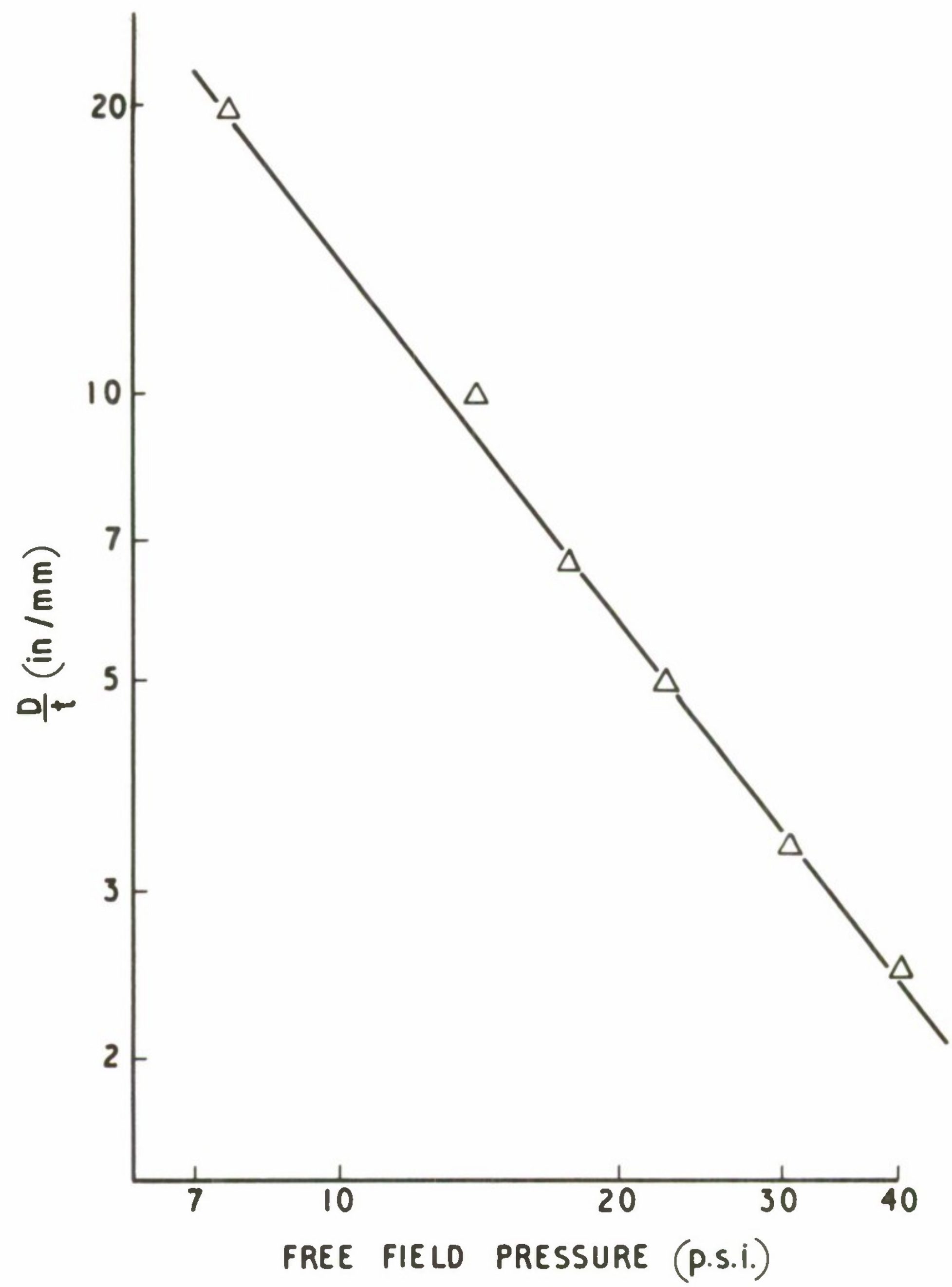

FIG. 9 CALIBRATION OF 0·16 in DIAMETER APERTURE USING 0·008 mm FOIL

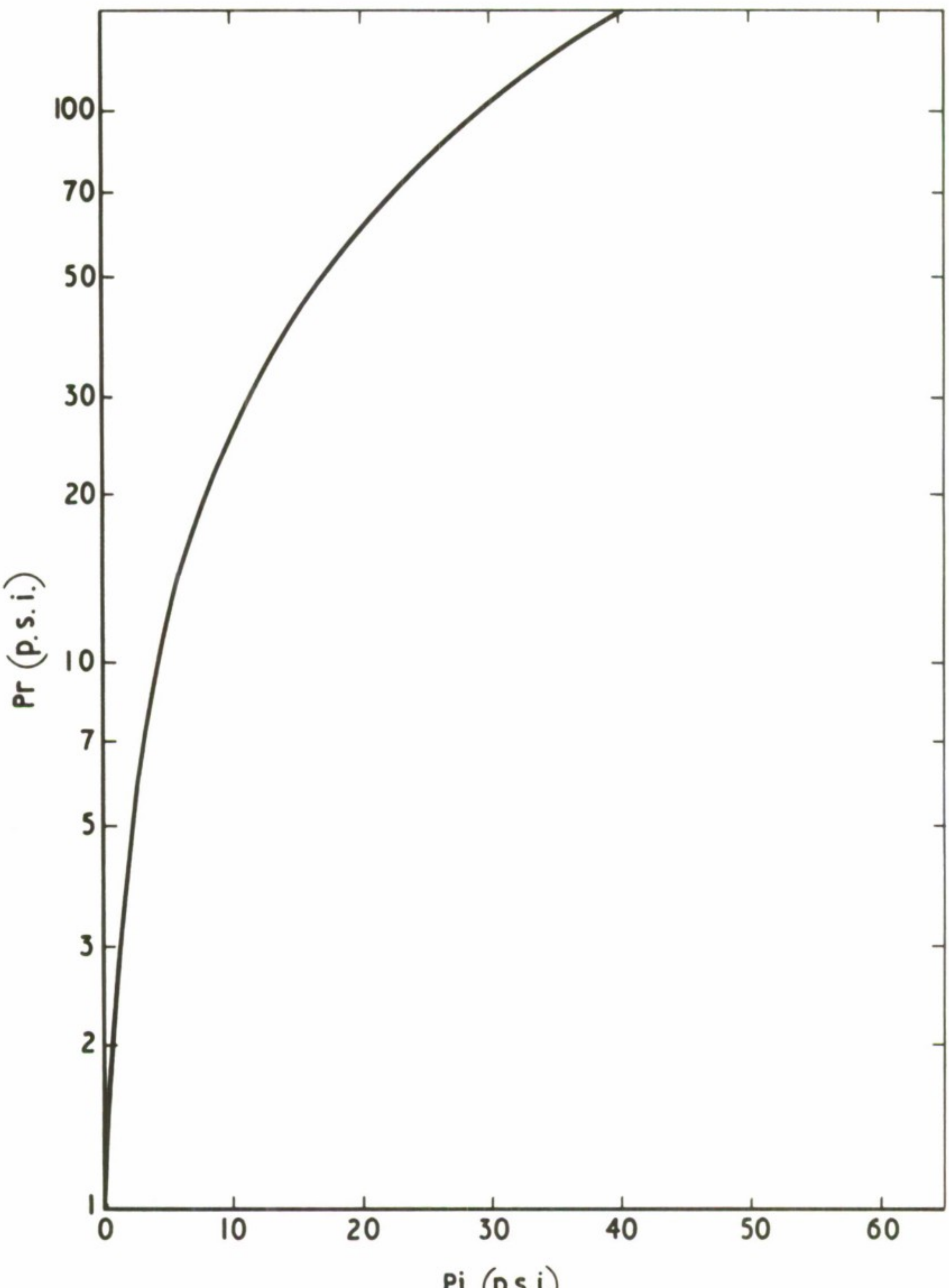

FIG. 10 RELATIONSHIP BETWEEN HYDROSTATIC OR SIDE-ON PRESSURE (Pi) IN BLAST WAVE AND THE REFLECTED PRESSURE (Pr) EXPERIENCED BY THE GAUGE

DIAM. OF DIAPHRAGM 'D' (in)	NO. OF FOILS 'n'	RATIO $\frac{D}{t}$ (t = .008 x n mm)	LOWEST PRESSURE FOR RUPTURE (p.s.i.)	HIGHEST PRESSURE FOR NON-RUPTURE (p.s.i.)
1.4	1	175	1.6	1.75
1.4	2	87.5	2.9	3.1
1.4	3	58.3	4.0	4.0
1.4	4	43.8	5.0	5.0
1.4	6	29.2	6.8	6.8
1.4	8	21.9	8.4	8.4
0.8	1	100	2.4	2.5
0.8	2	50	4.4	4.3
0.8	3	33.3	5.8	5.8
0.8	4	25	8.0	8.2
0.8	6	16.7	9.6	10.5
0.8	8	12.5	14.0	14.0
0.32	1	40	5.1	5.5
0.32	2	20	9.5	9.8
0.32	3	13.3	12.5	13.0
0.32	4	10	16.5	16.5
0.32	6	6.67	21.0	23.0
0.32	8	5	30.0	29.0
0.16	1	20	7.2	7.9
0.16	2	10	14.0	14.0
0.16	3	6.67	17.5	18.0
0.16	4	5	22.0	23.0
0.16	6	3.33	30.0	31.0
0.16	8	2.5	41.0	40.0

FIG. 11 RUPTURE PRESSURES FOR VARIOUS APERTURE DIAMETERS, AND A RANGE OF DIAPHRAGM THICKNESSES (USING STANDARD .008 mm FOILS)

FIG. 12

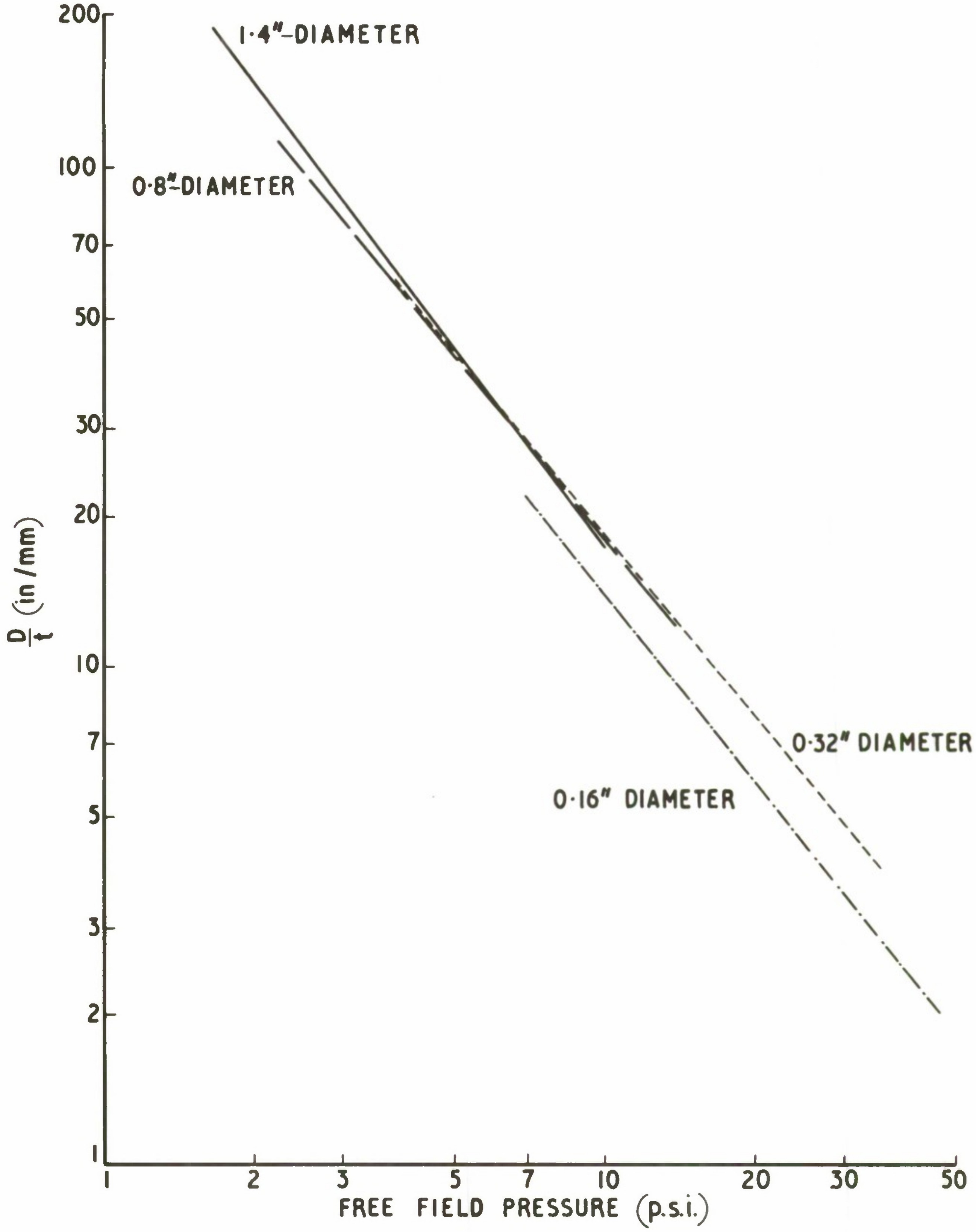

FIG. 12 COMPARISON OF CALIBRATION OF DIFFERENT APERTURE DIAMETERS (USING 0·008 mm FOIL)

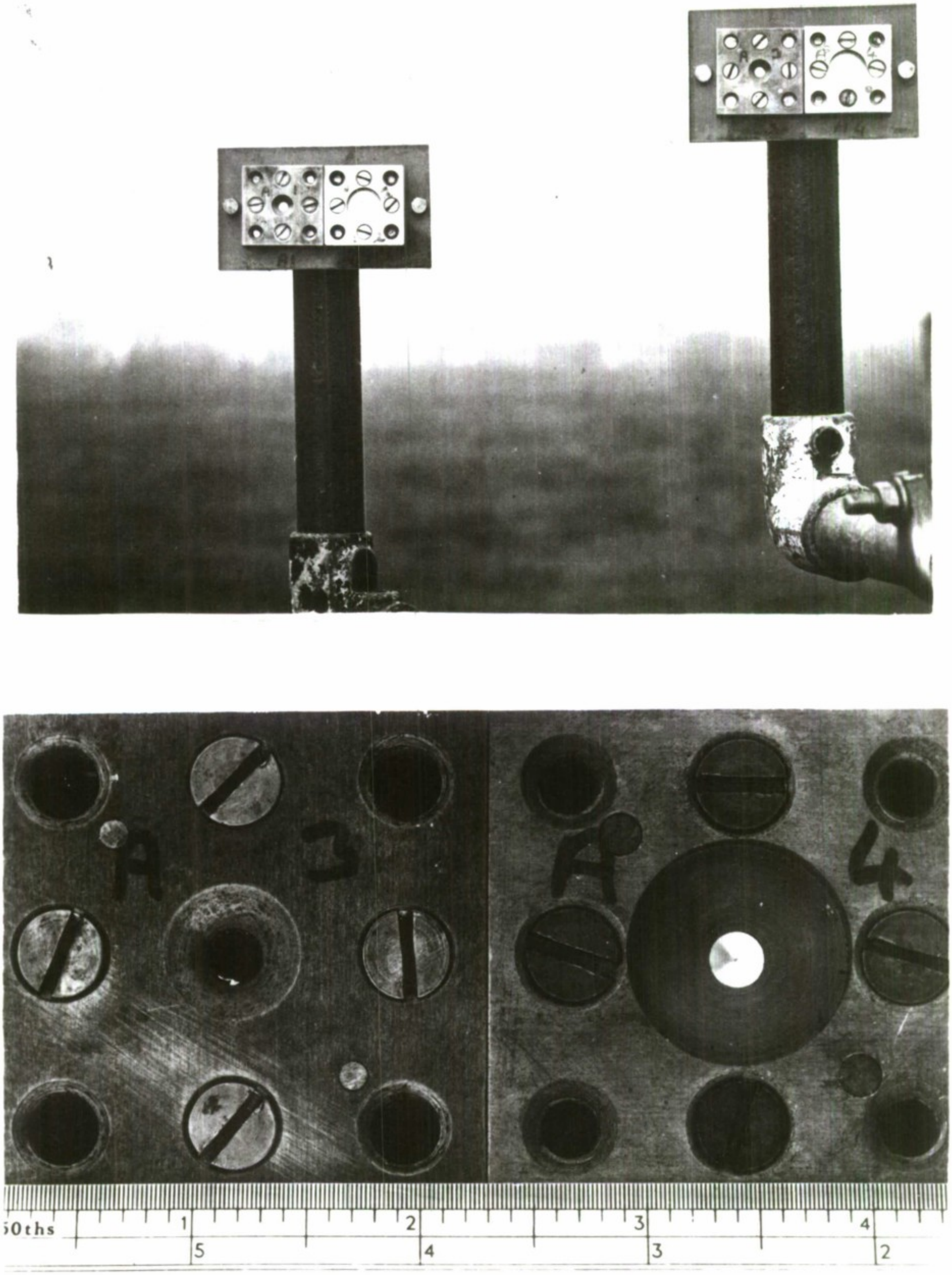

FIG. 13 COMPARISON OF APERTURE SHAPES

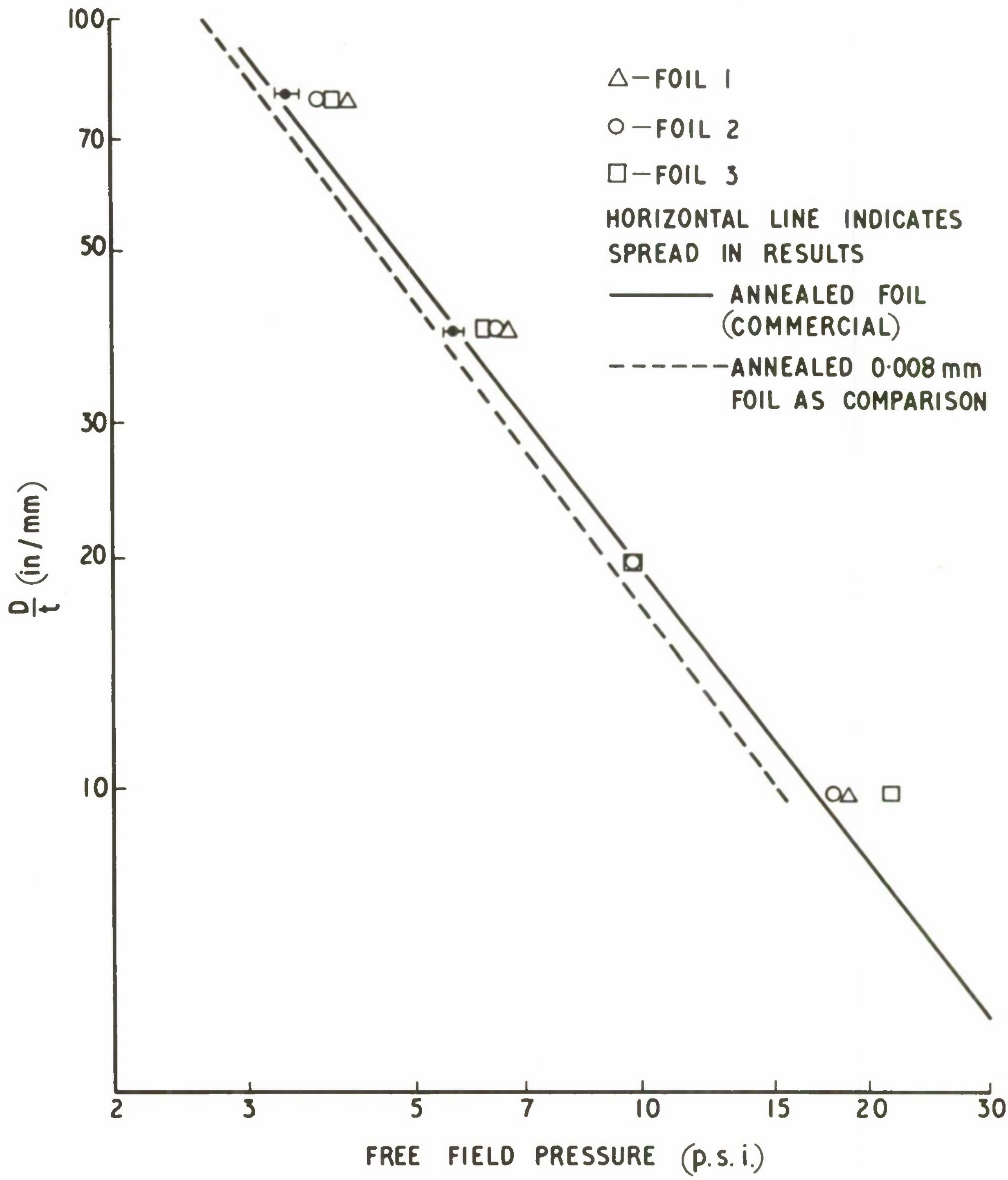

FIG. 14 COMPARISON OF STANDARD 0·008 mm FOIL AND 0·016—0·019 mm ANNEALED COMMERCIAL FOIL IN 1·4 in DIAMETER APERTURE

FIG. 15

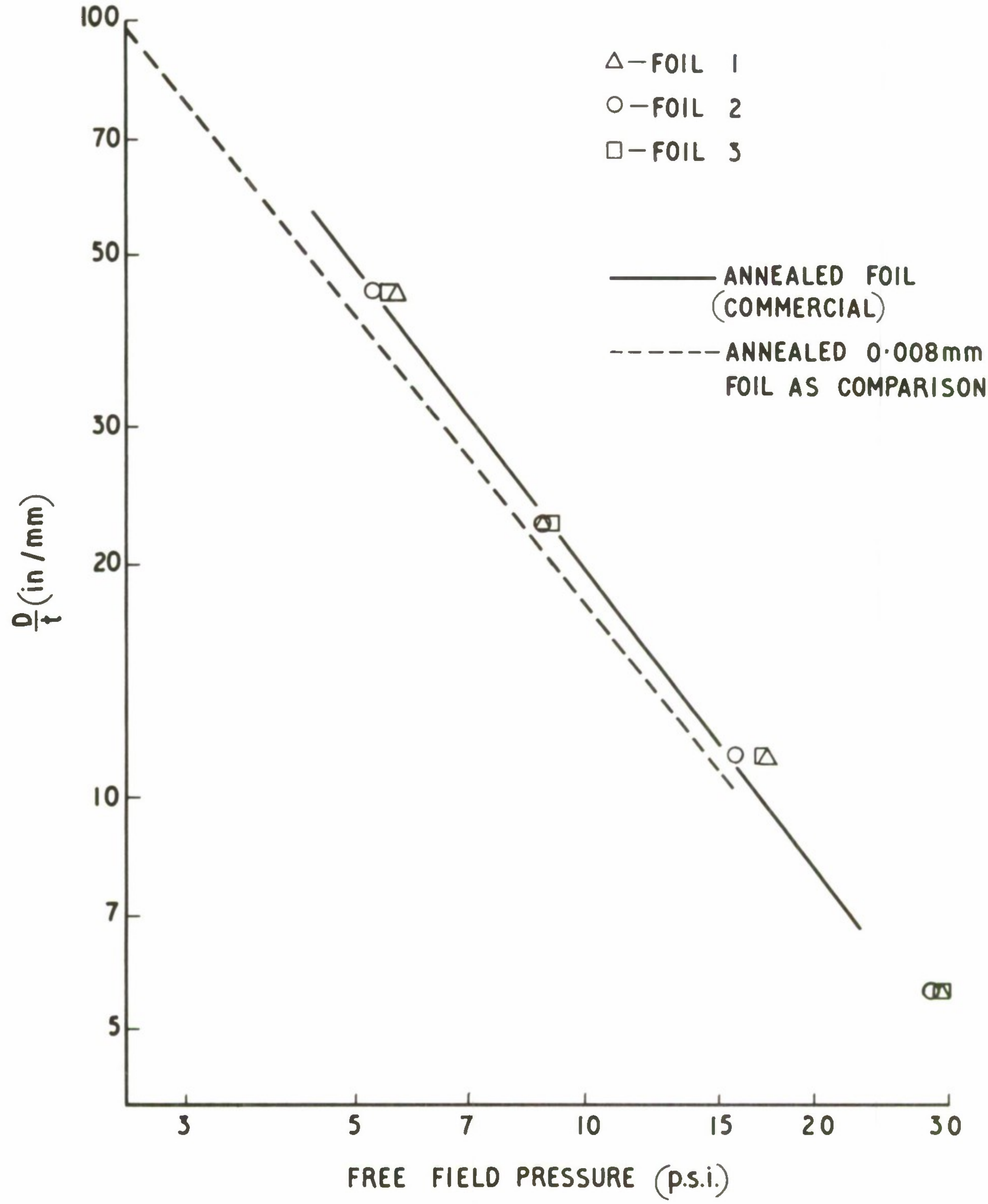

FIG. 15 COMPARISON OF STANDARD 0·008 mm FOIL AND 0·016–0·019mm ANNEALED COMMERCIAL FOIL IN 0·8 in DIAMETER APERTURE

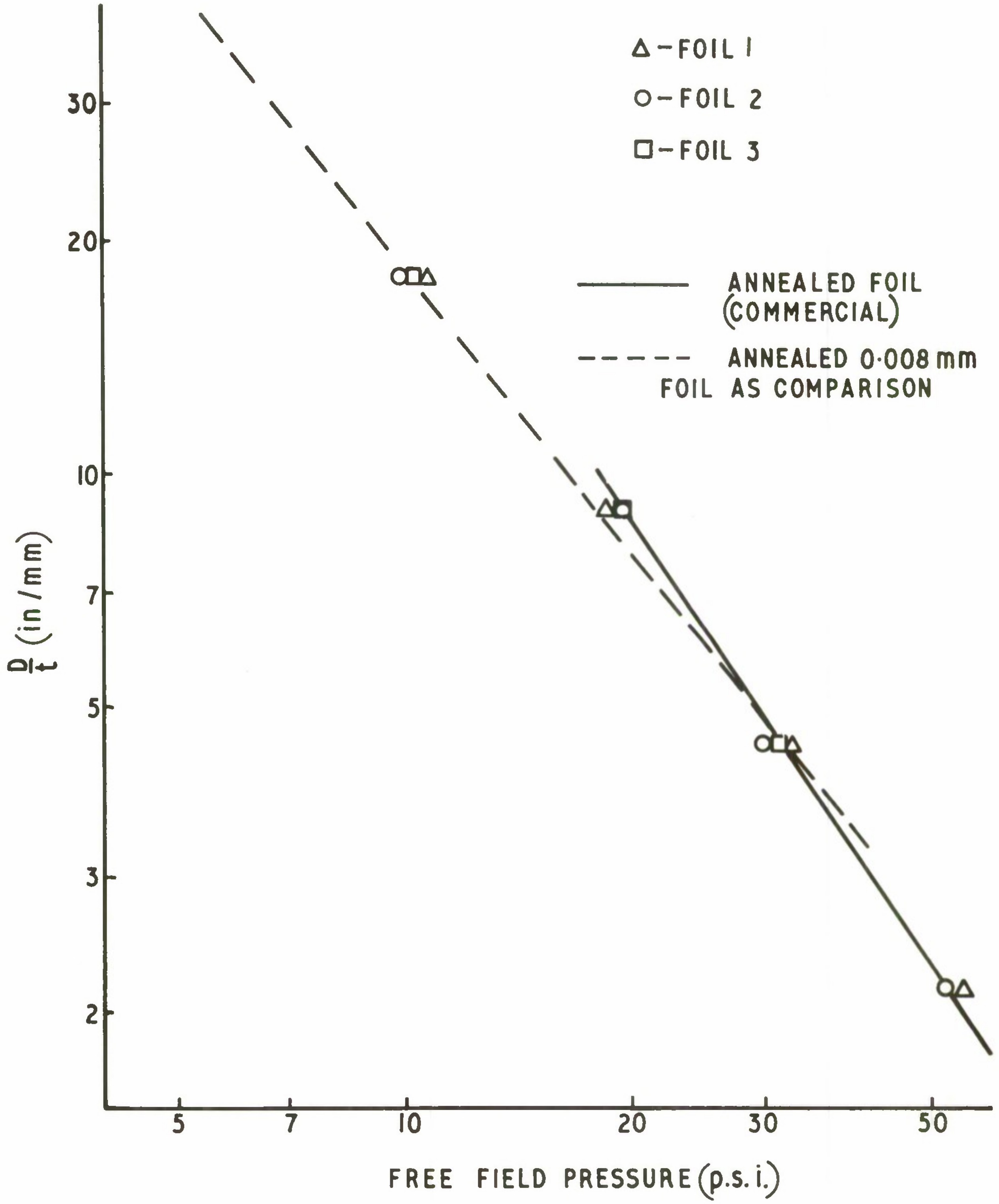

FIG.16 COMPARISON OF STANDARD 0·008 mm FOIL AND 0·016 – 0·019 mm ANNEALED COMMERCIAL FOIL IN 0·8 in DIAMETER APERTURE

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Item 1.2 Piezo-electric measurement of gun blast pressures

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FIG.1

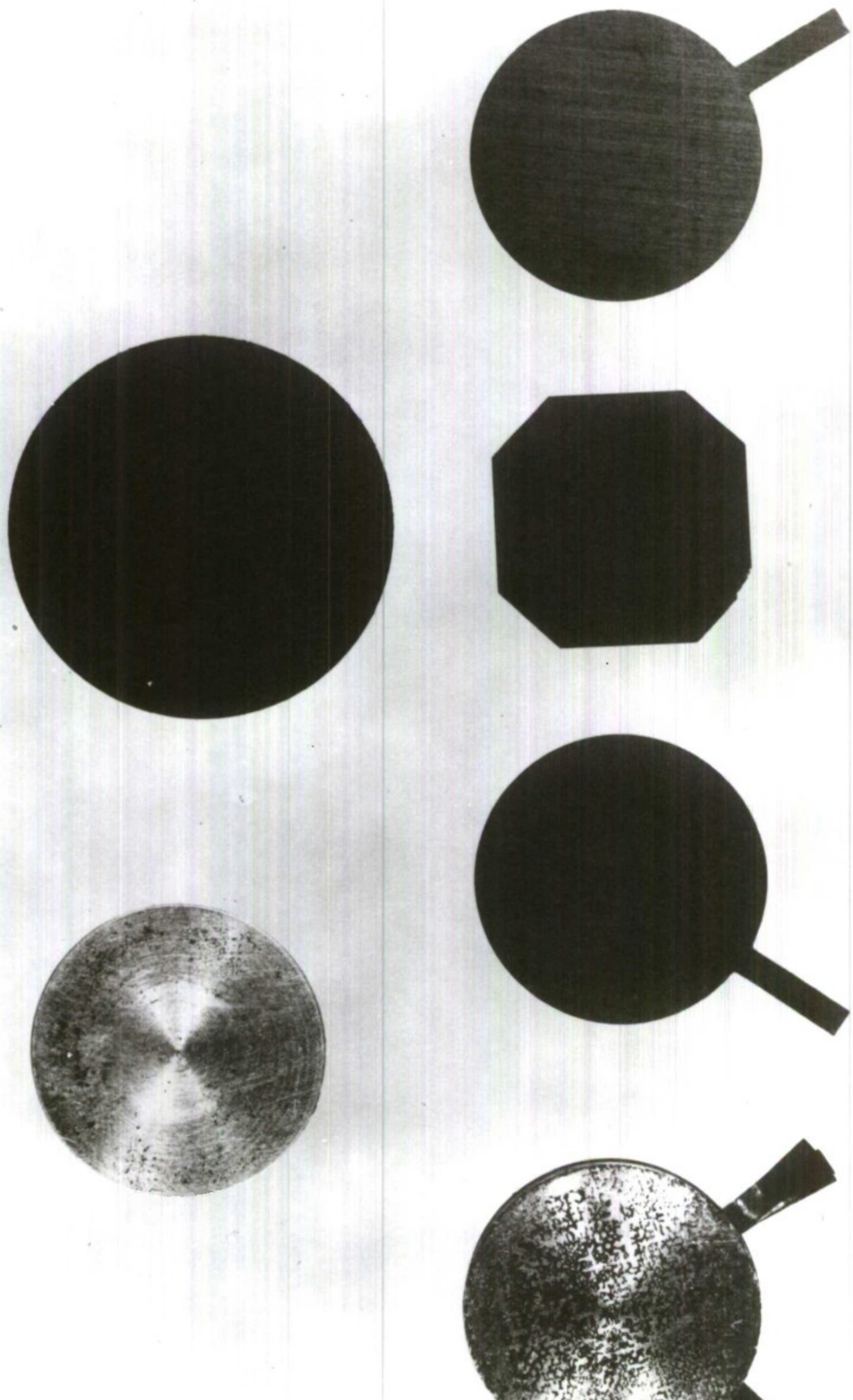

FIG.1 ASSEMBLY OF 12-CRYSTAL BLAST GAUGES

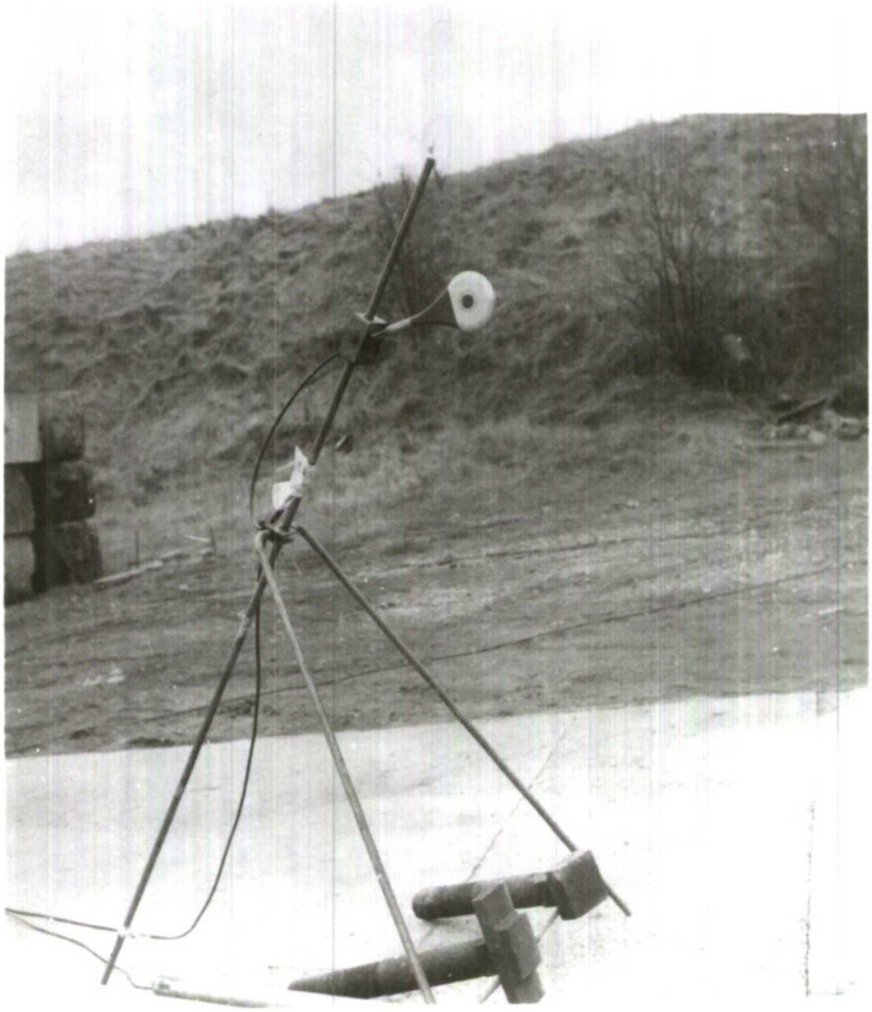

FIG. 2 MOUNTING STAND FOR GAUGES

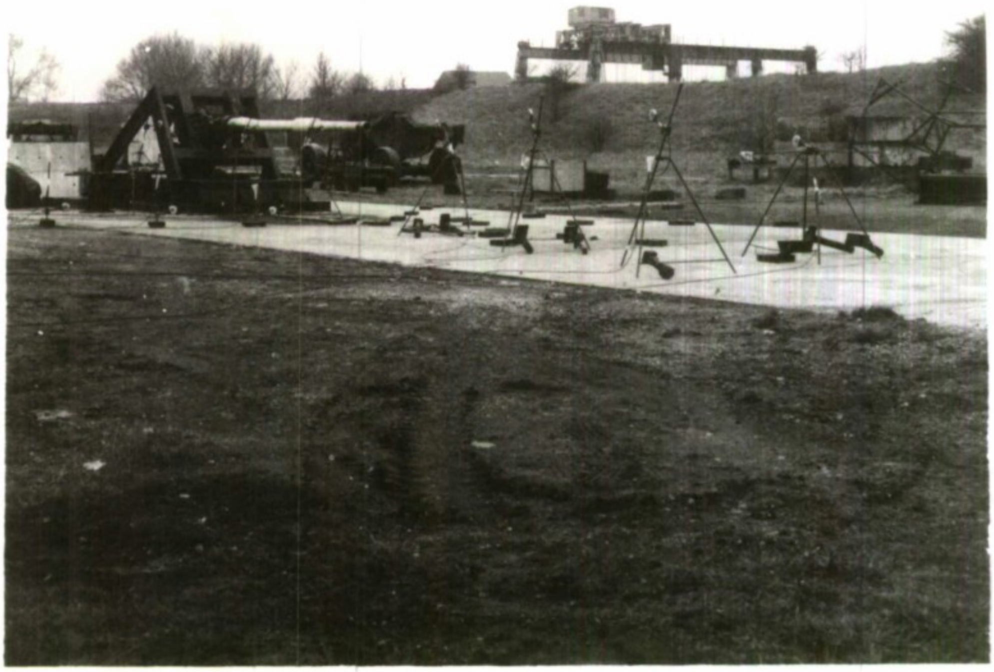

FIG. 3 LAYOUT OF GAUGES FOR A TYPICAL TRIAL

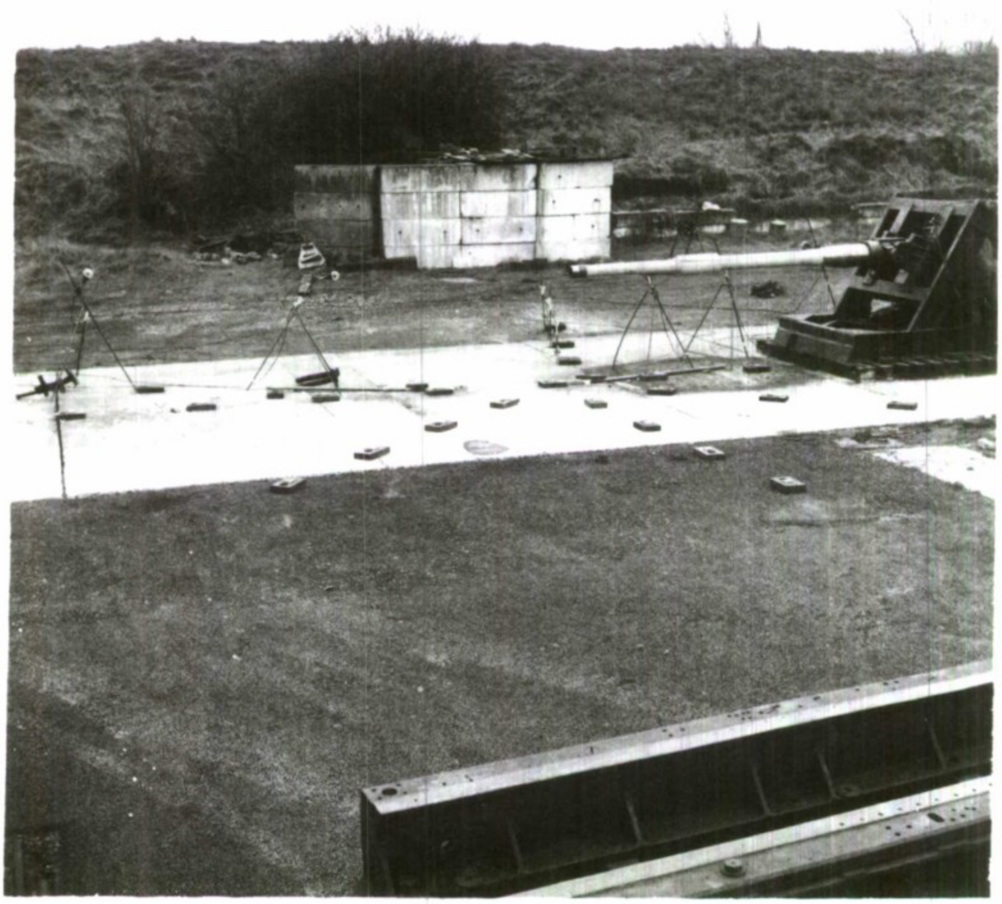

FIG. 4 LAYOUT OF GAUGES FOR A TYPICAL TRIAL

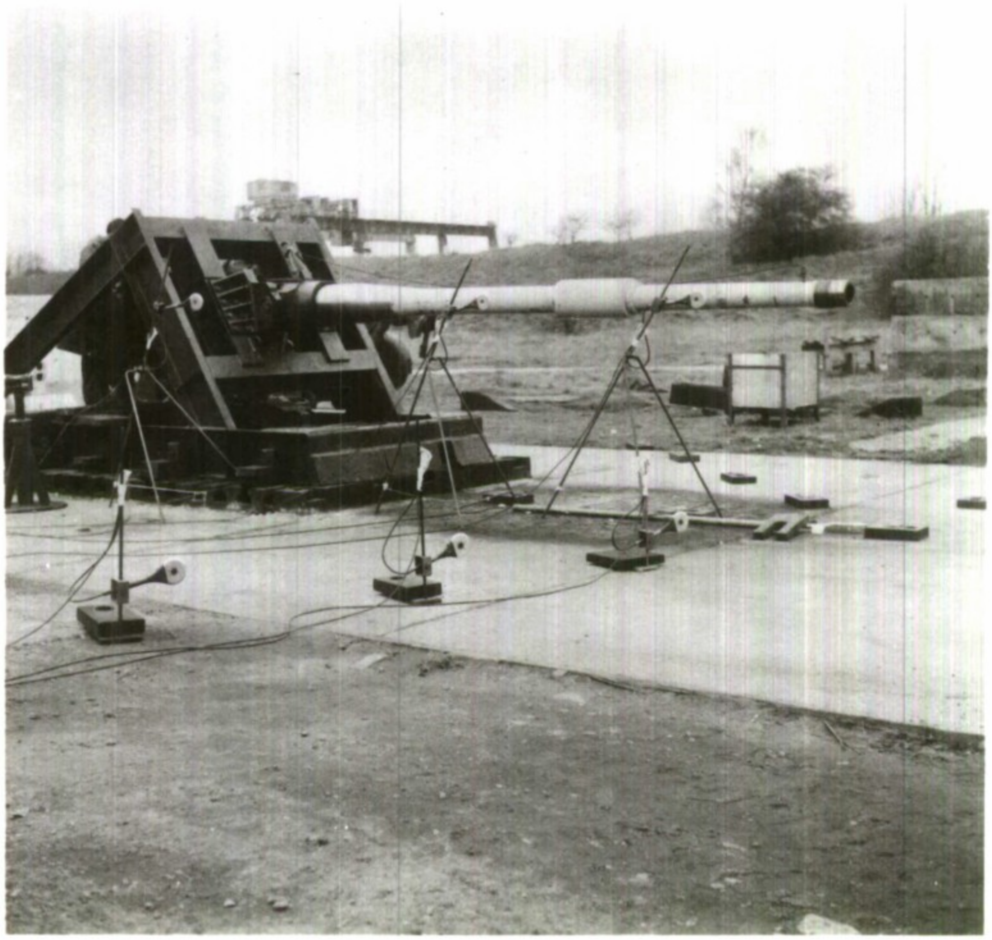

FIG. 5 LAYOUT OF GAUGES FOR A TYPICAL TRIAL

FIG.6

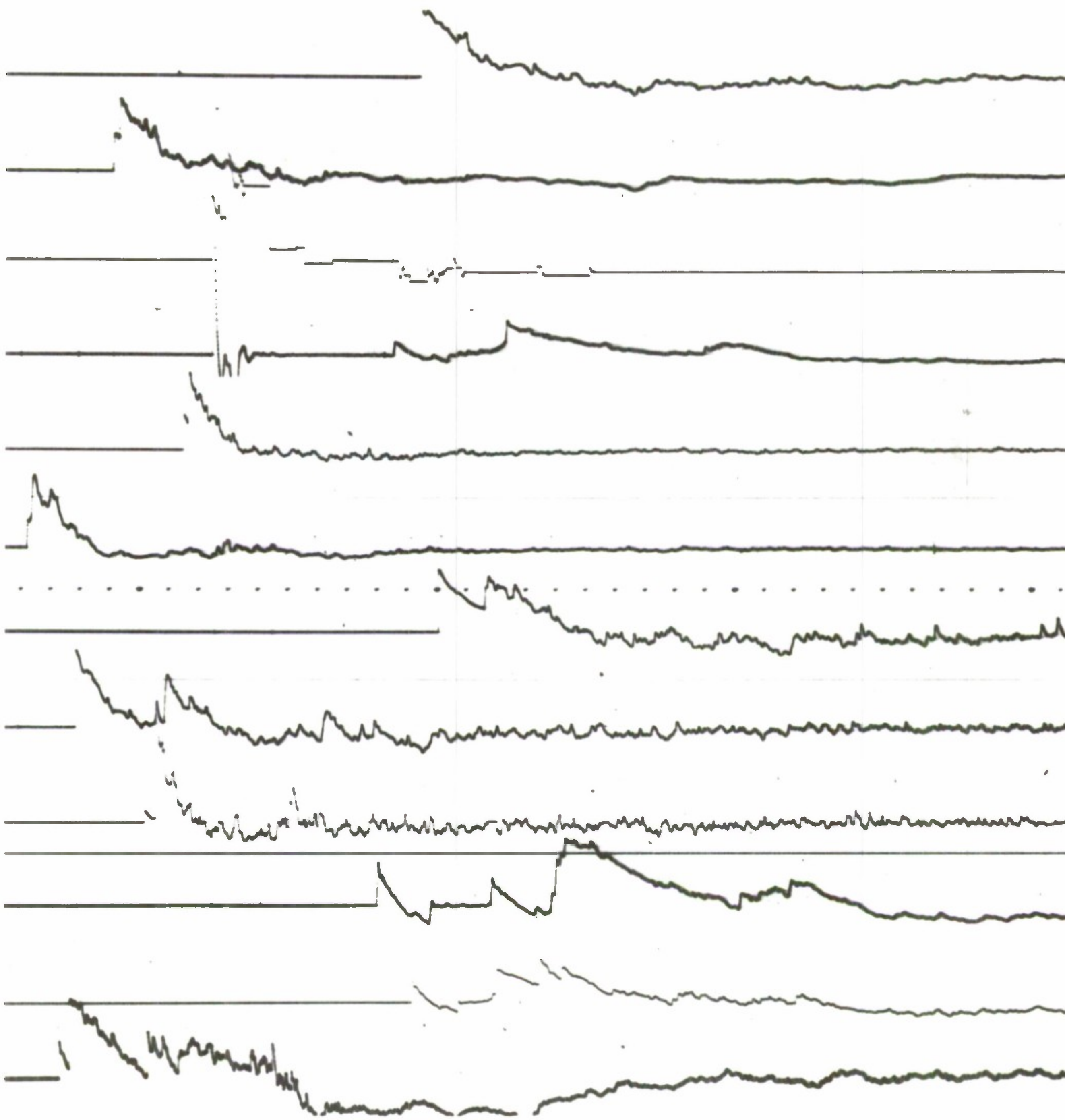

FIG. 6 TYPICAL BLAST OSCILLOGRAMS

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Item 3 Muzzle Brake Model Studies

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FIG. 1

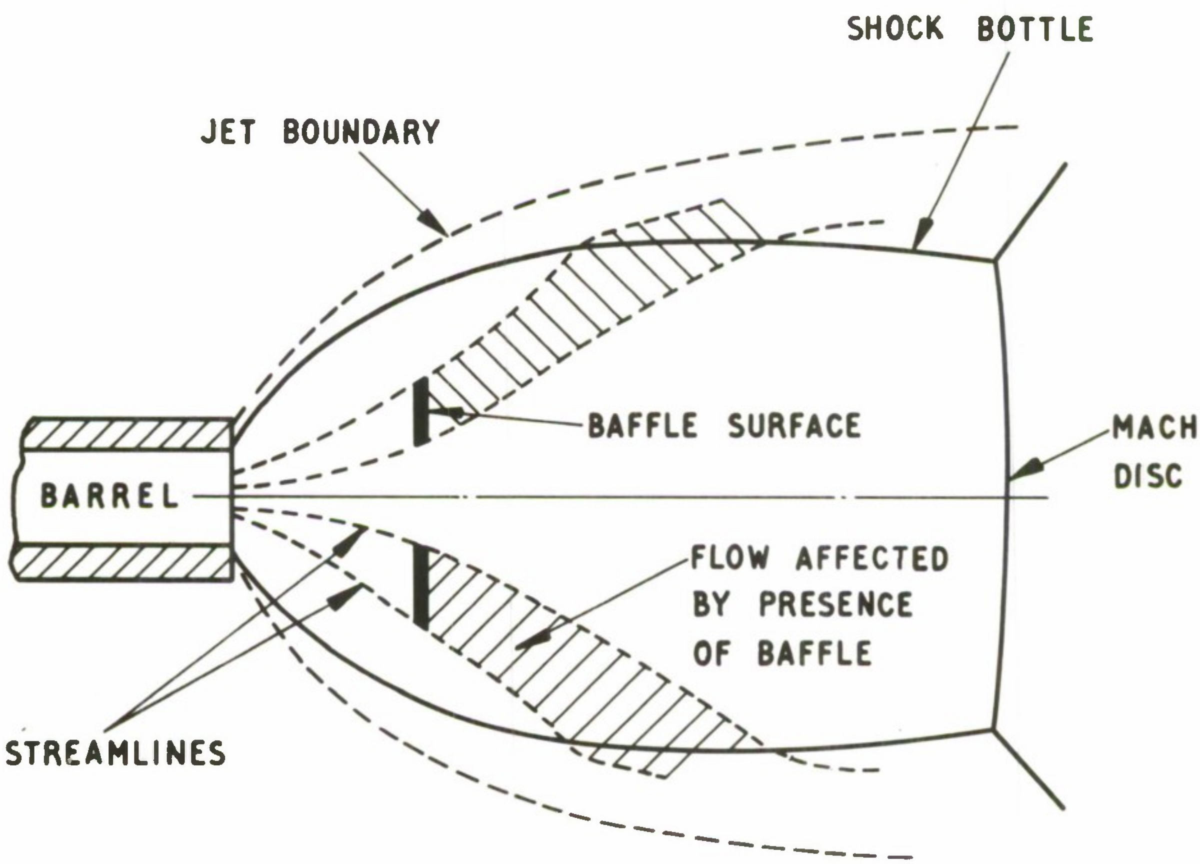


FIG. 1 FREE JET EXPANSION FROM GUN BARREL AND FLOW AFFECTED BY A BAFFLE SURFACE

FIG. 2

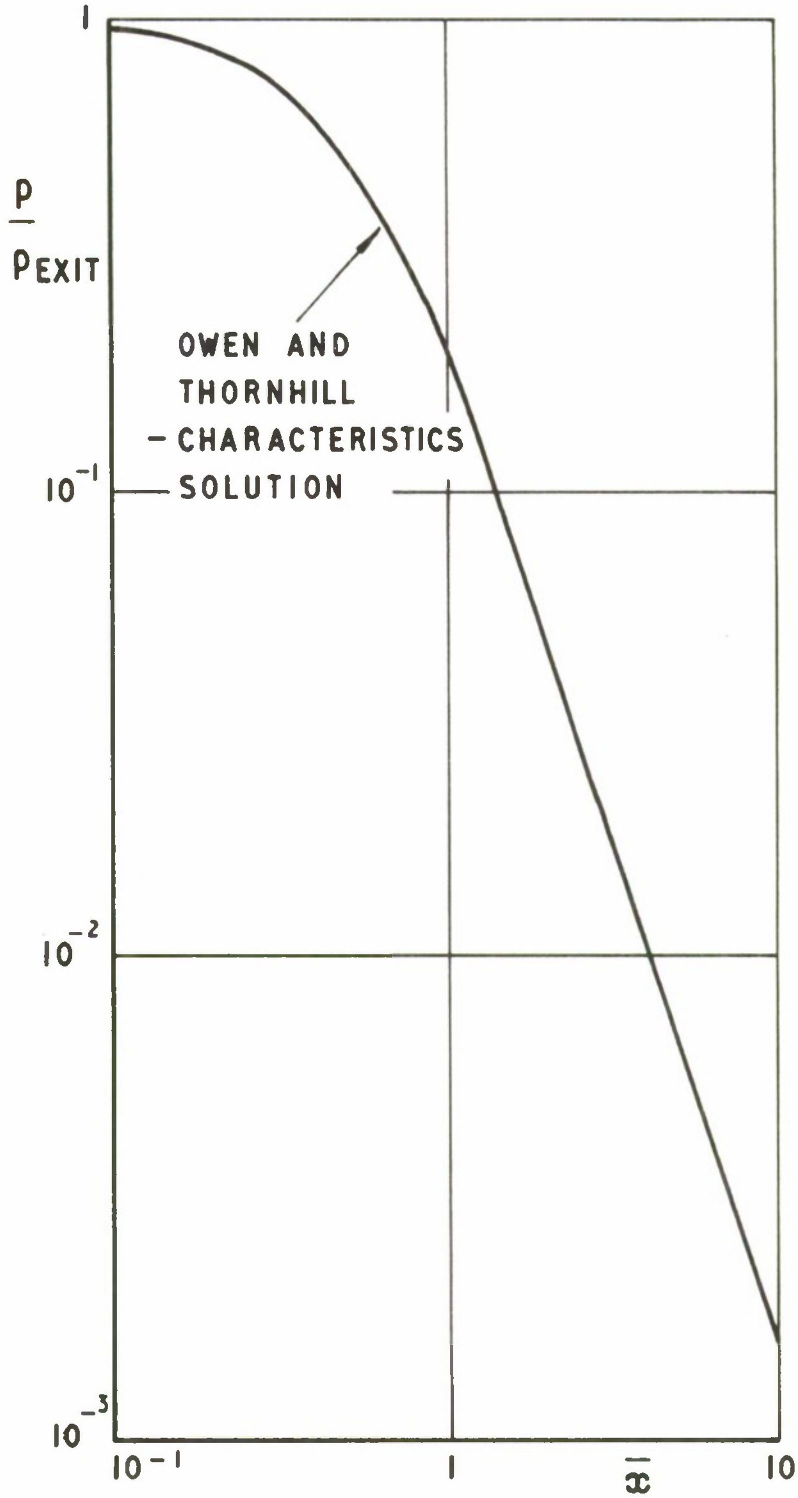


FIG. 2 AXIAL VARIATION OF $\frac{p}{p_{EXIT}}$ WITH $\bar{x}$

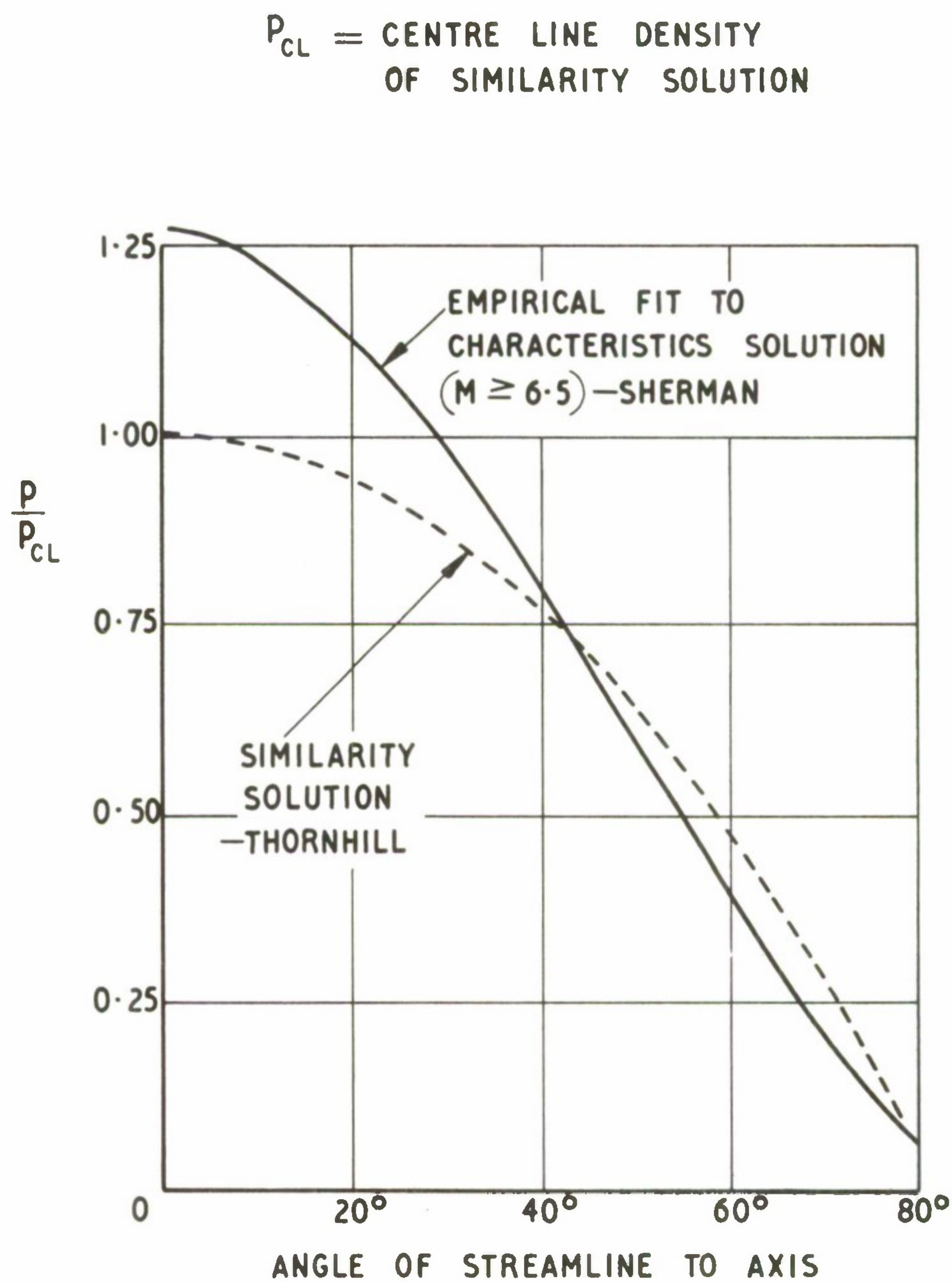


FIG. 3 AZIMUTHAL VARIATION OF DENSITY

FIG. 4

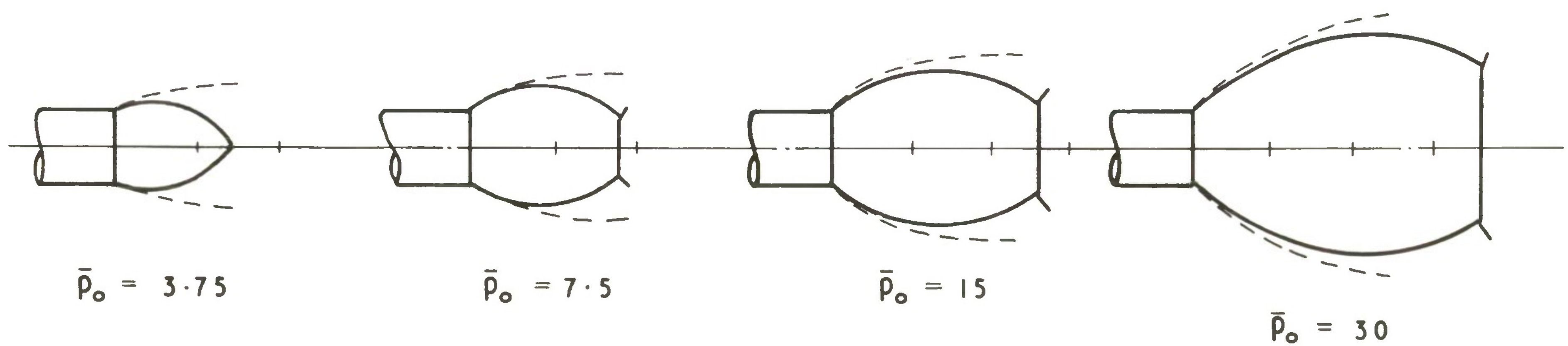
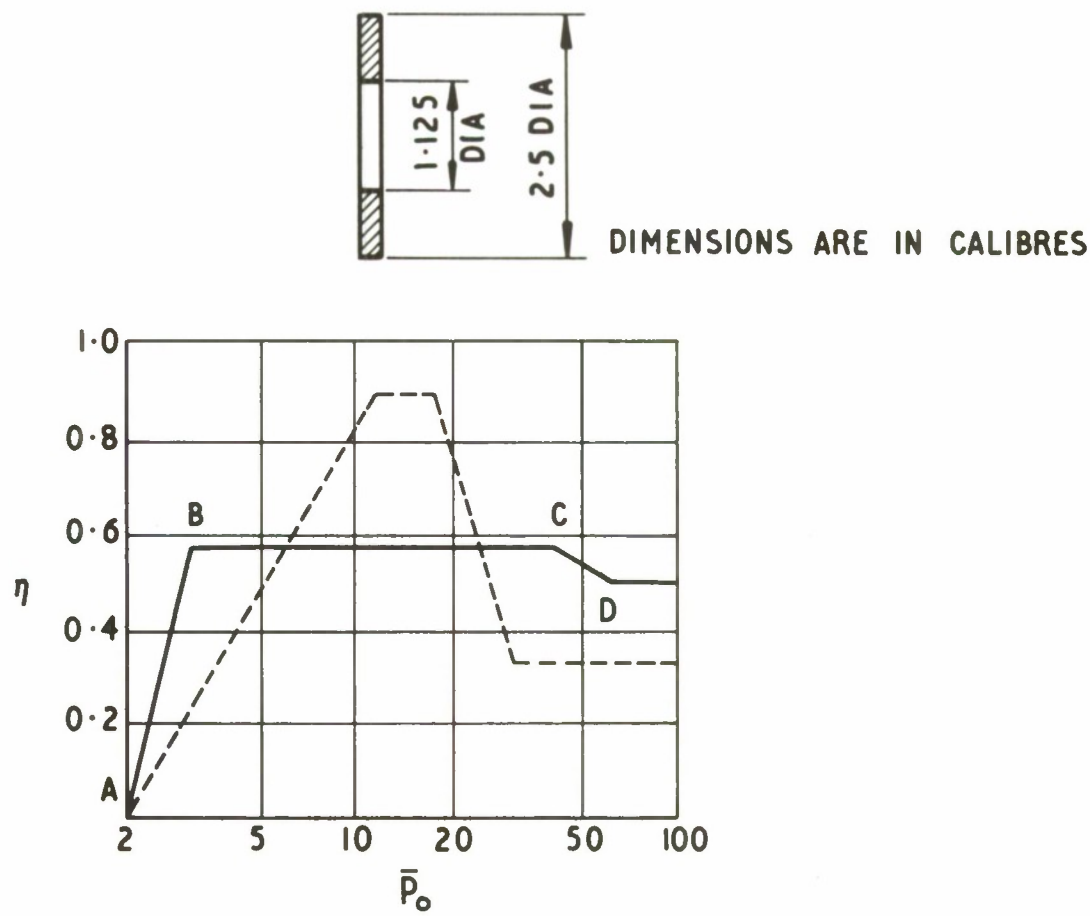


FIG. 4 DEVELOPMENT OF SHOCK BOTTLE AND JET BOUNDARY WITH $\bar{p}_o$

FIG. 5



———— $\bar{x} = 1 \cdot 0$ CALIBRES FROM MUZZLE

- - - - - $\bar{x} = 2 \cdot 5$ CALIBRES FROM MUZZLE

FIG. 5 THEORETICAL VARIATION OF η WITH $\bar{P}_o$

FIG. 6

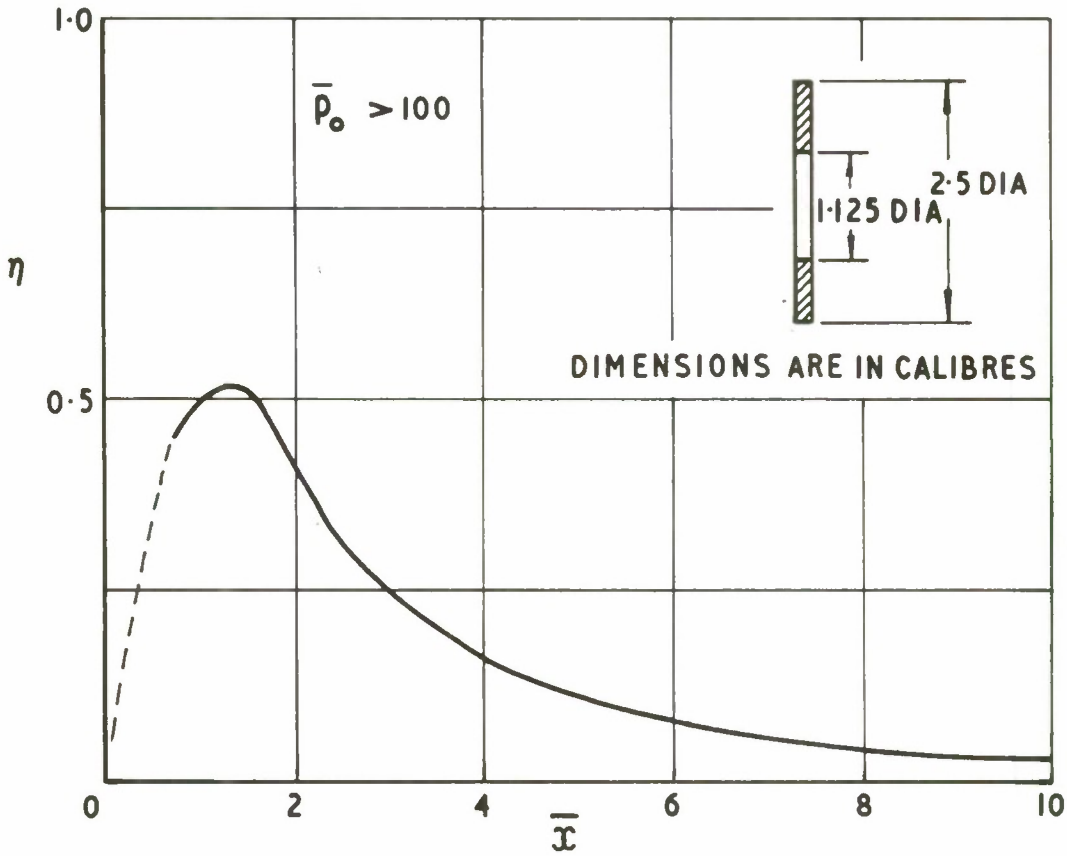


FIG. 6 THEORETICAL VARIATION OF η WITH $\bar{x}$

FIG. 7

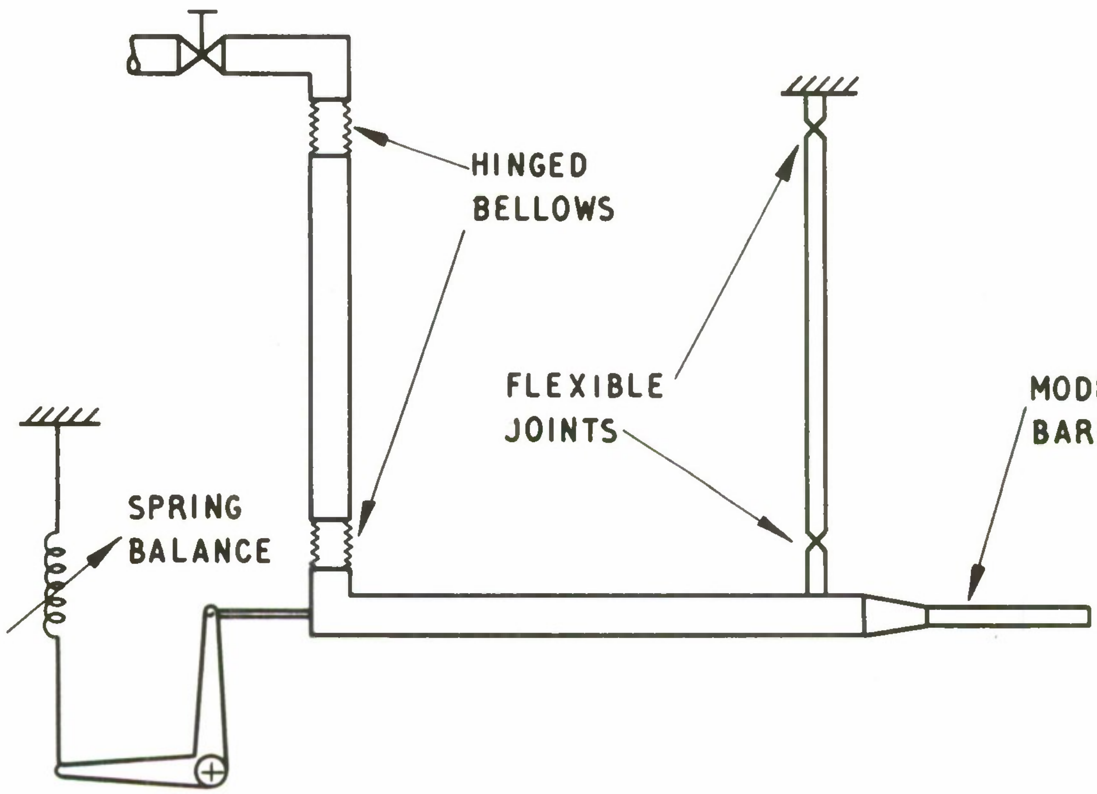


FIG. 7 TEST RIG FOR MODEL MUZZLE BRAKES

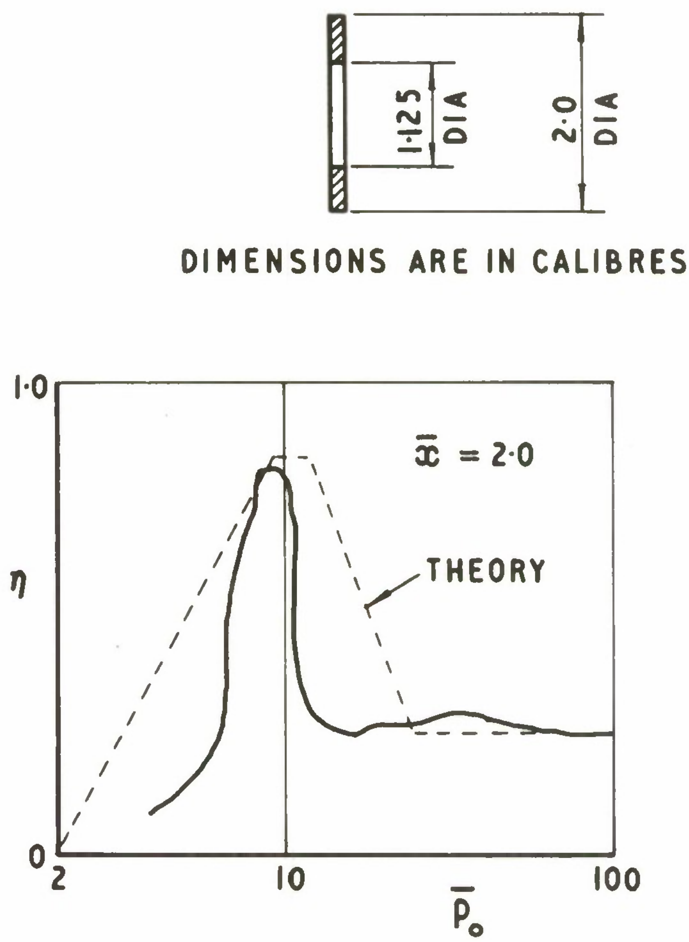


FIG. 8 (a) COMPARISON OF THEORY AND EXPERIMENT VARYING $\bar{p}_o$

FIG. 8 (b)

P_o = CHAMBER PRESSURE

P_1, P_2 = PRESSURES ON FRONT AND REAR OF BAFFLE

P_∞ = AMBIENT PRESSURE

$\bar{P}_o$ = $P_o \div P_\infty$

r = RADIUS

r_j = RADIUS OF BARREL

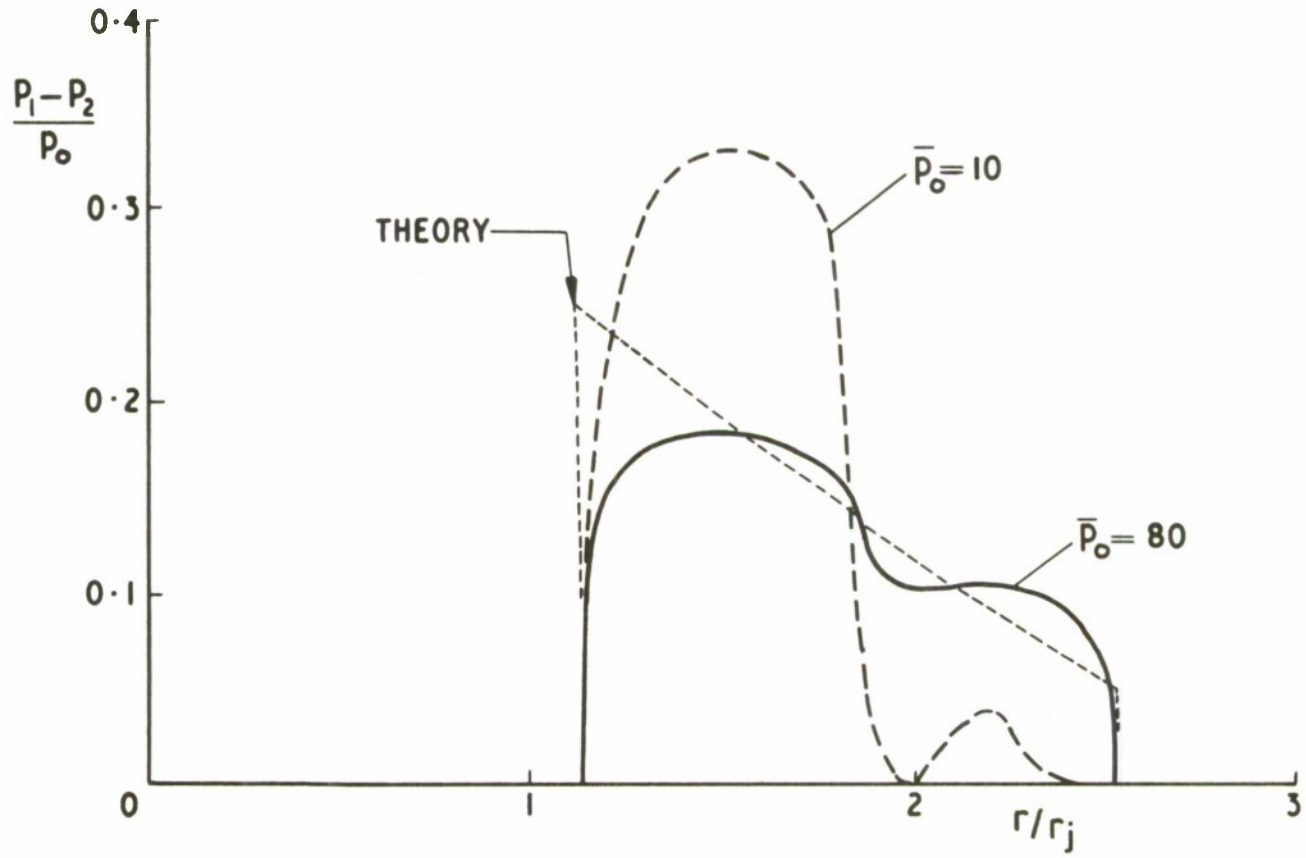


FIG. 8(b) TYPICAL PRESSURE DISTRIBUTION ACROSS BAFFLE BE 1·0

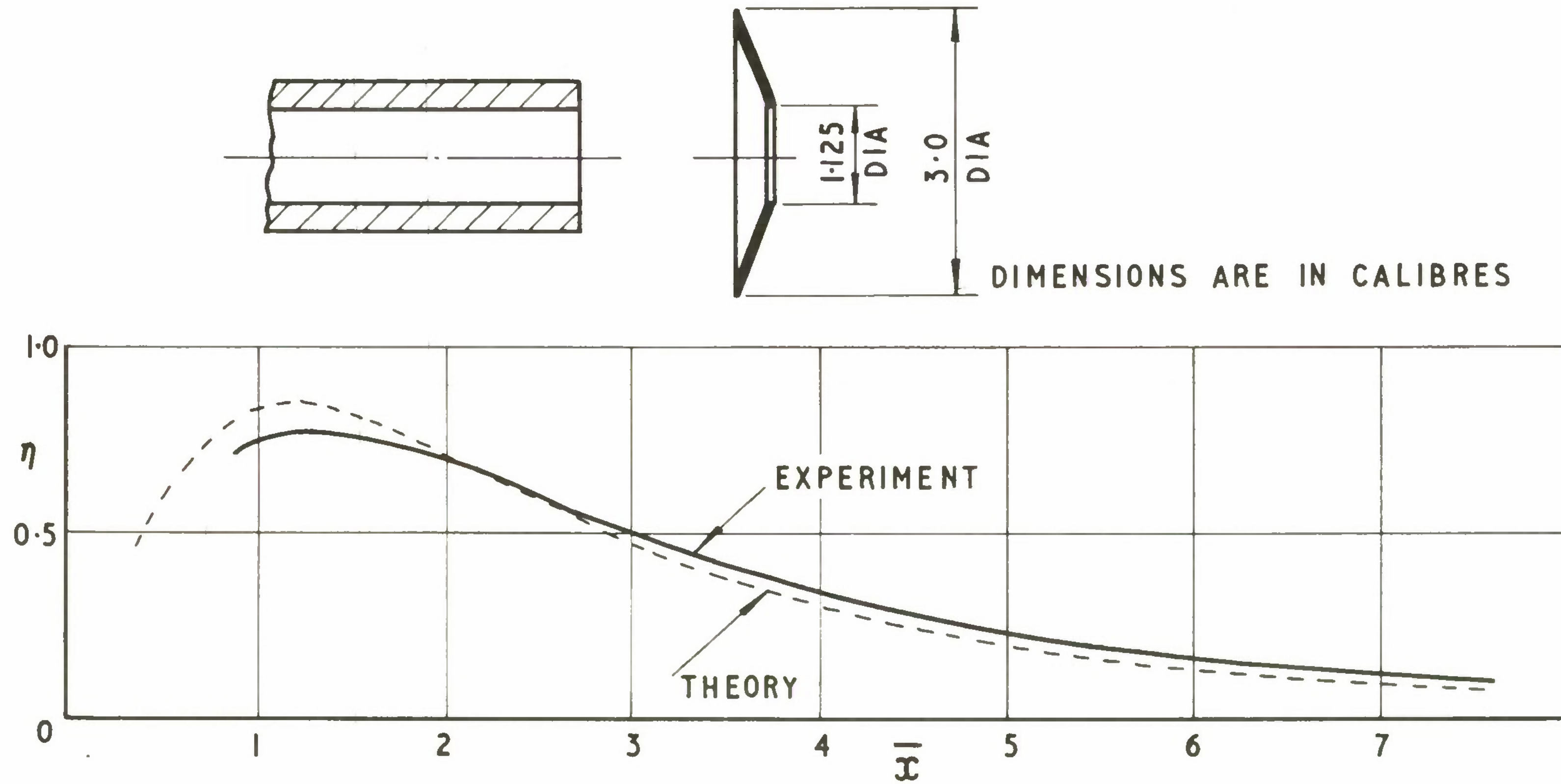
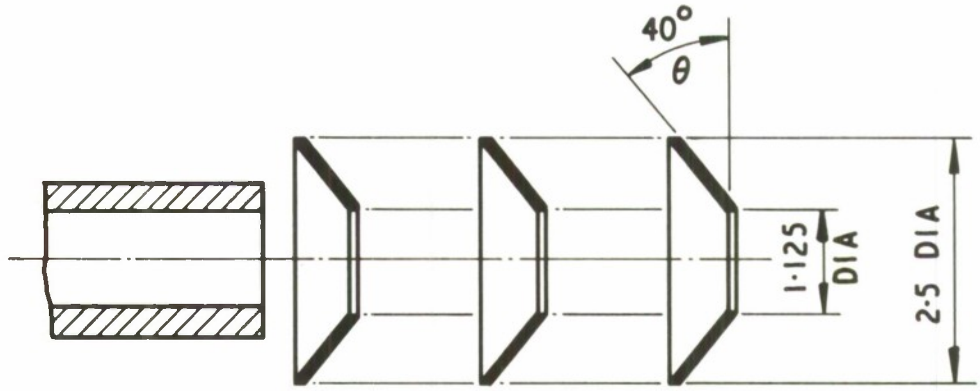


FIG. 9 COMPARISON OF THEORY AND EXPERIMENT VARYING $\bar{x}$

FIG. 10



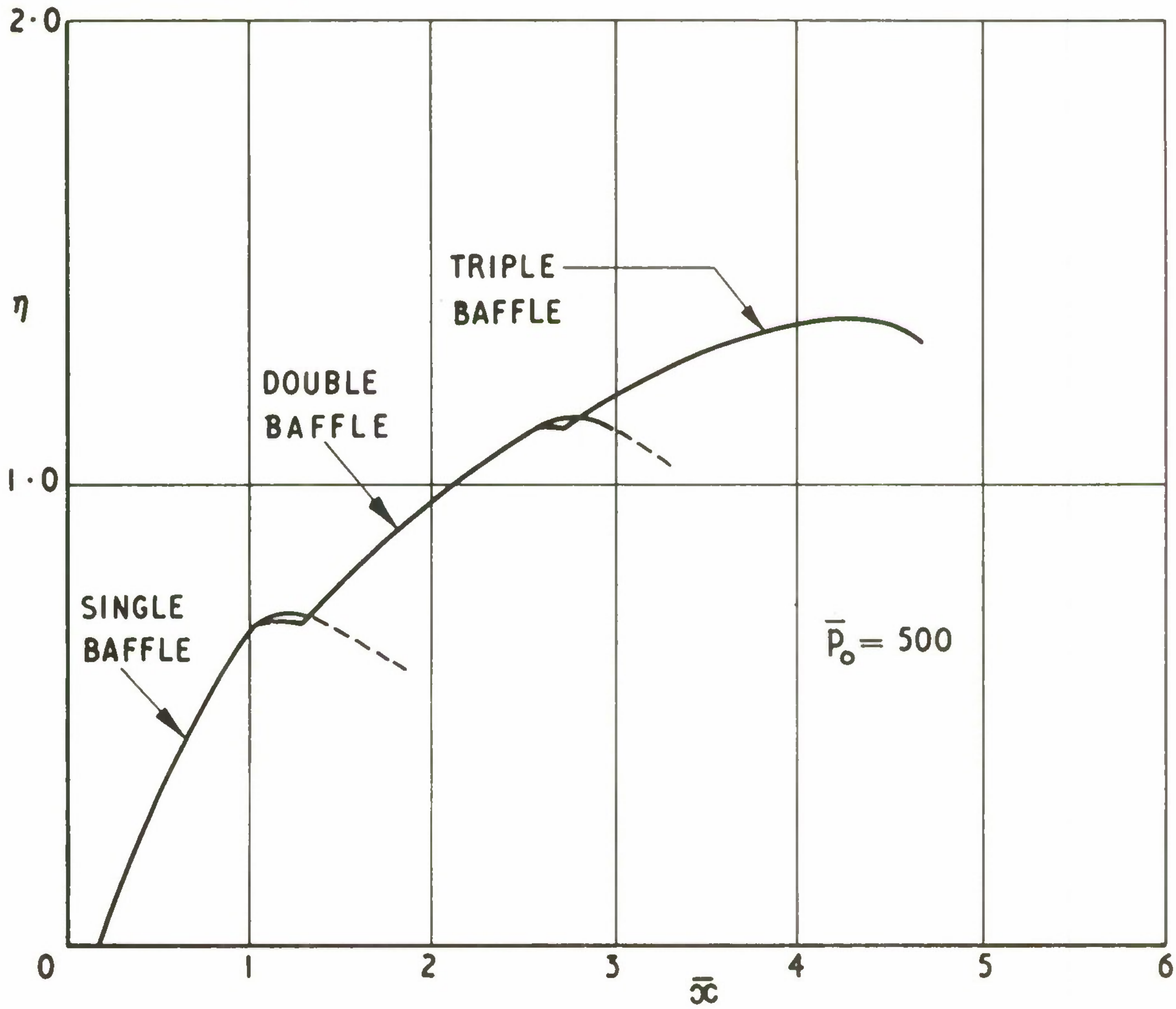


FIG. 10 EFFICIENCY OF MULTIPLE BAFFLES

FIG. 11

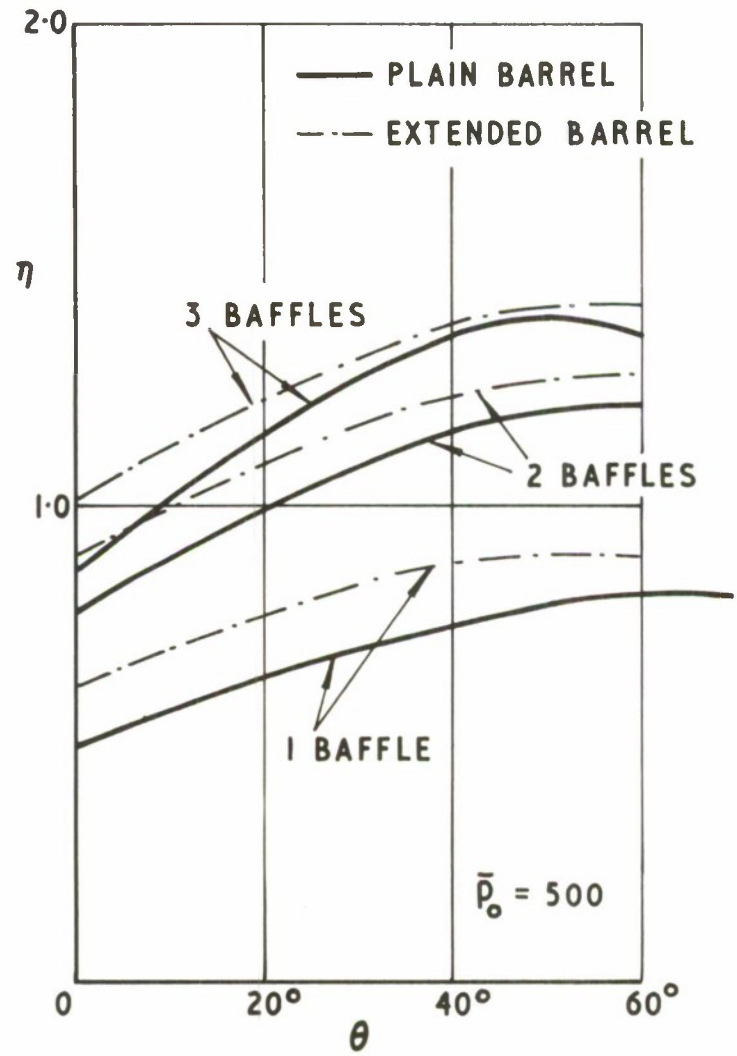


FIG. 11 MULTIPLE BAFFLES — OPTIMUM η

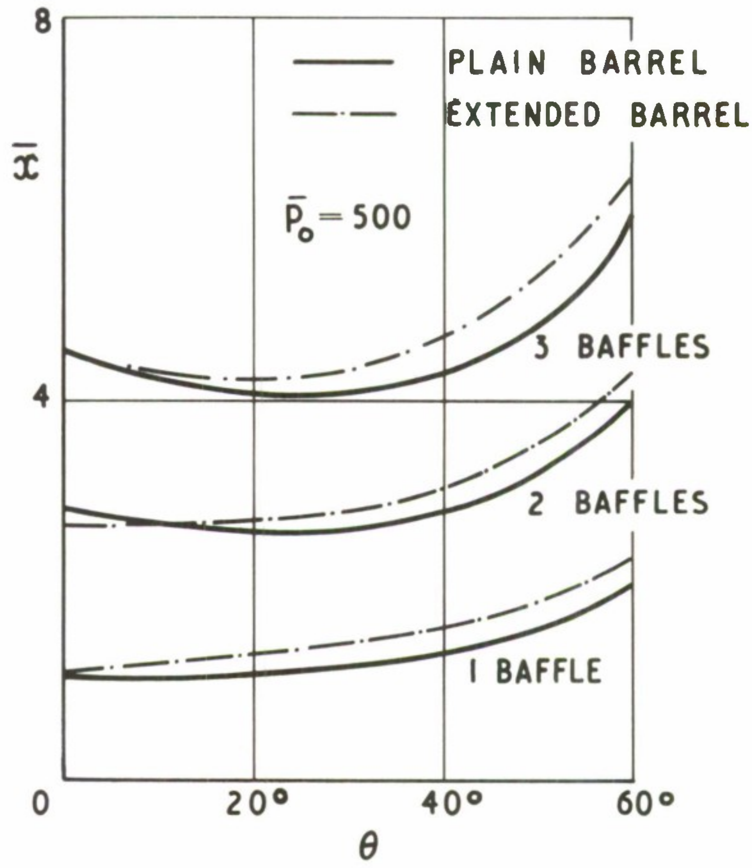
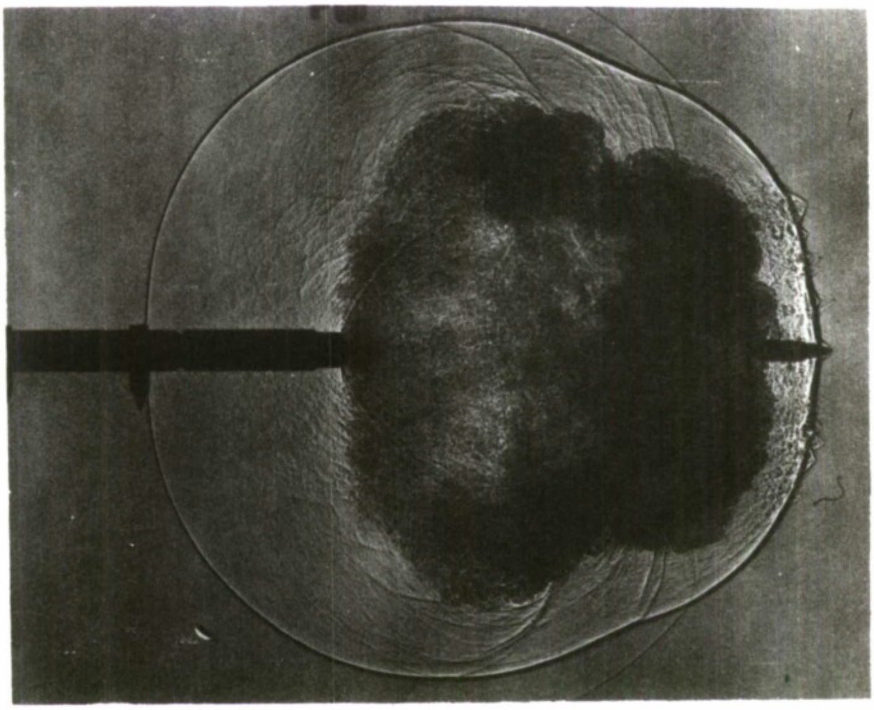
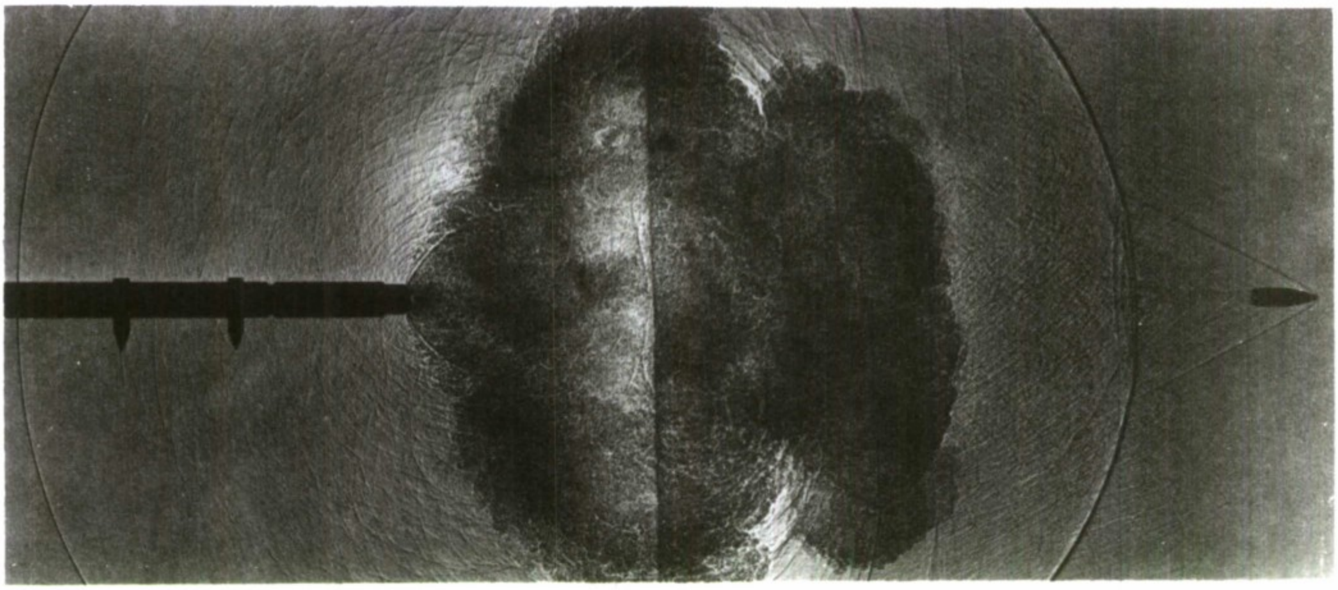


FIG. 12 MULTIPLE BAFFLES — OPTIMUM POSITION

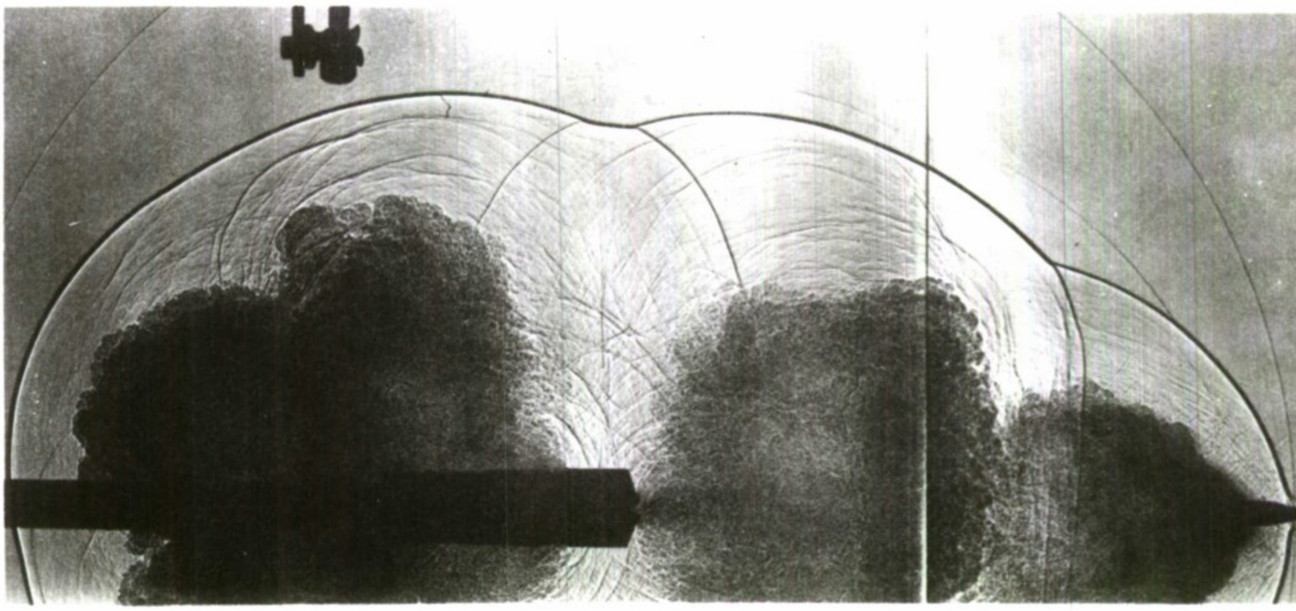


(a)

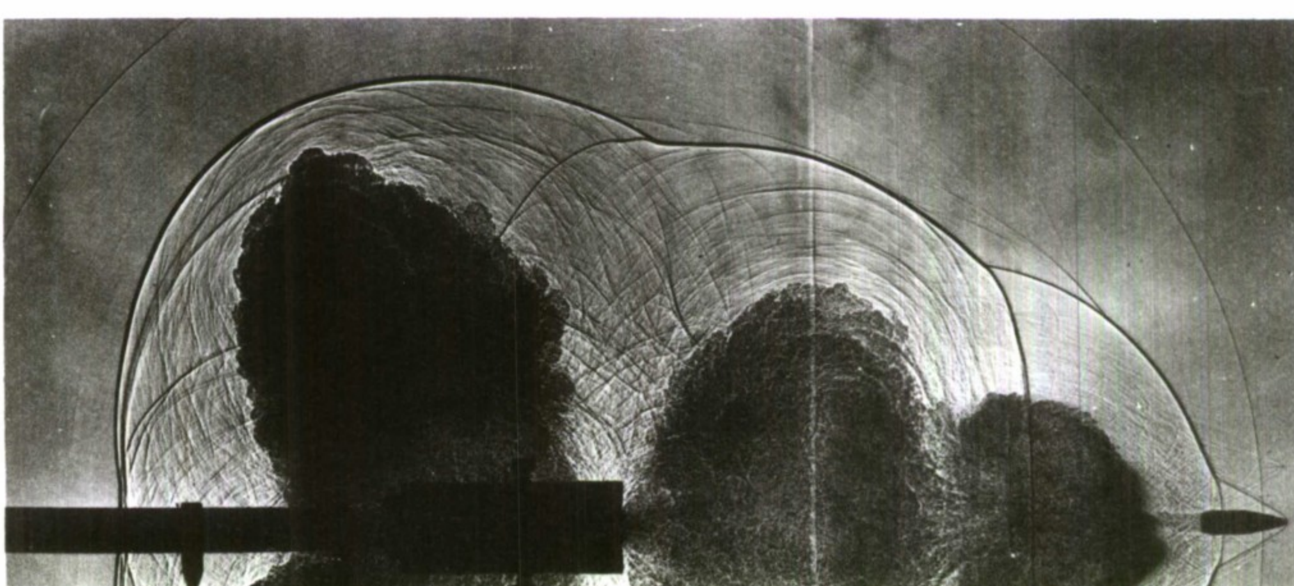


(b)

FIGS. 13 (a)(b) NO MUZZLE BRAKE — TWO TIME DELAYS



(c) BRAKE CEJ (20) L 1·5



(d) BRAKE CEJ (20) M 1·5

FIGS. 13(c)(d) COWLED BRAKES

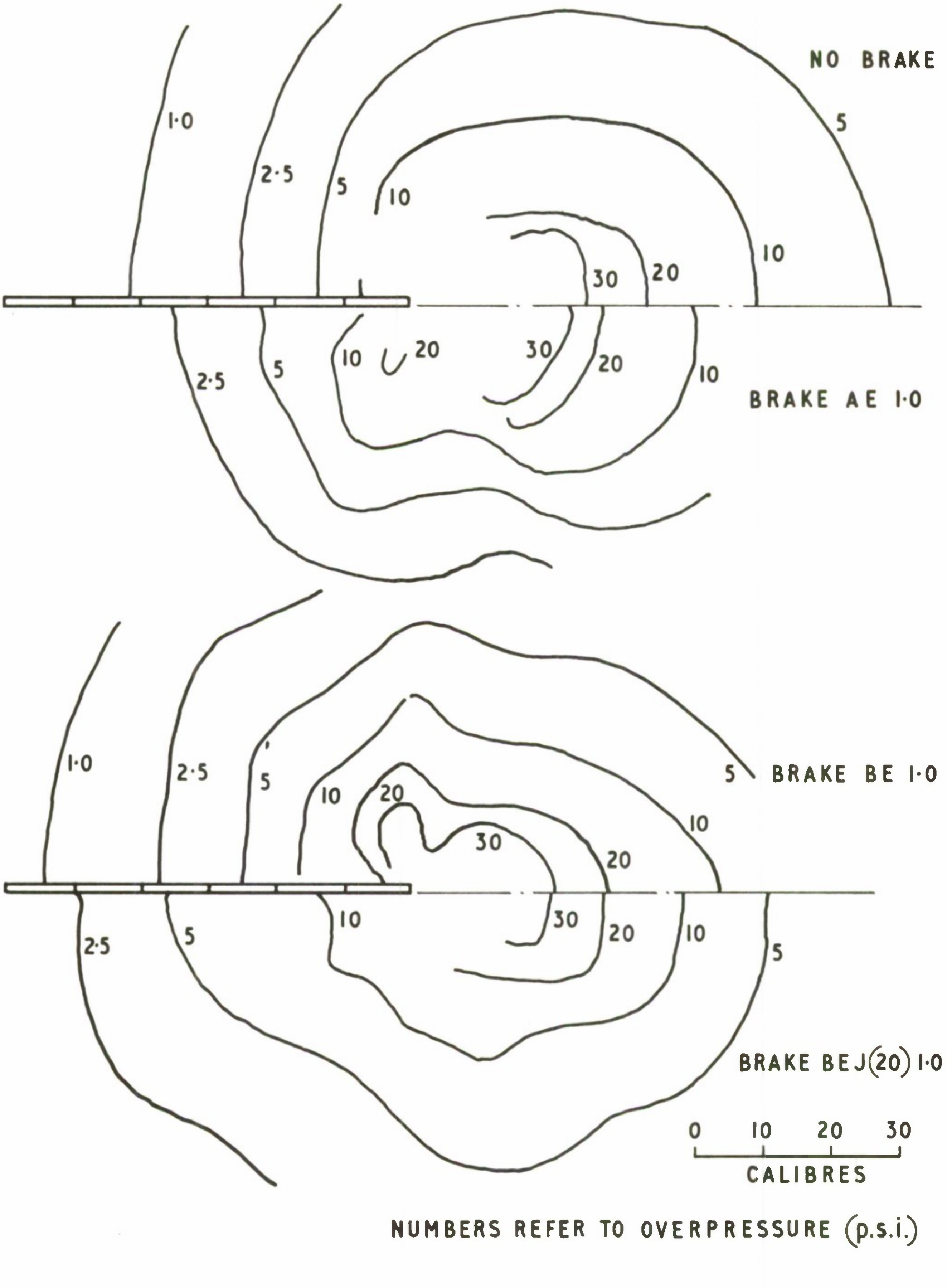


FIG. 14 CONTOURS OF BLAST OVERPRESSURES

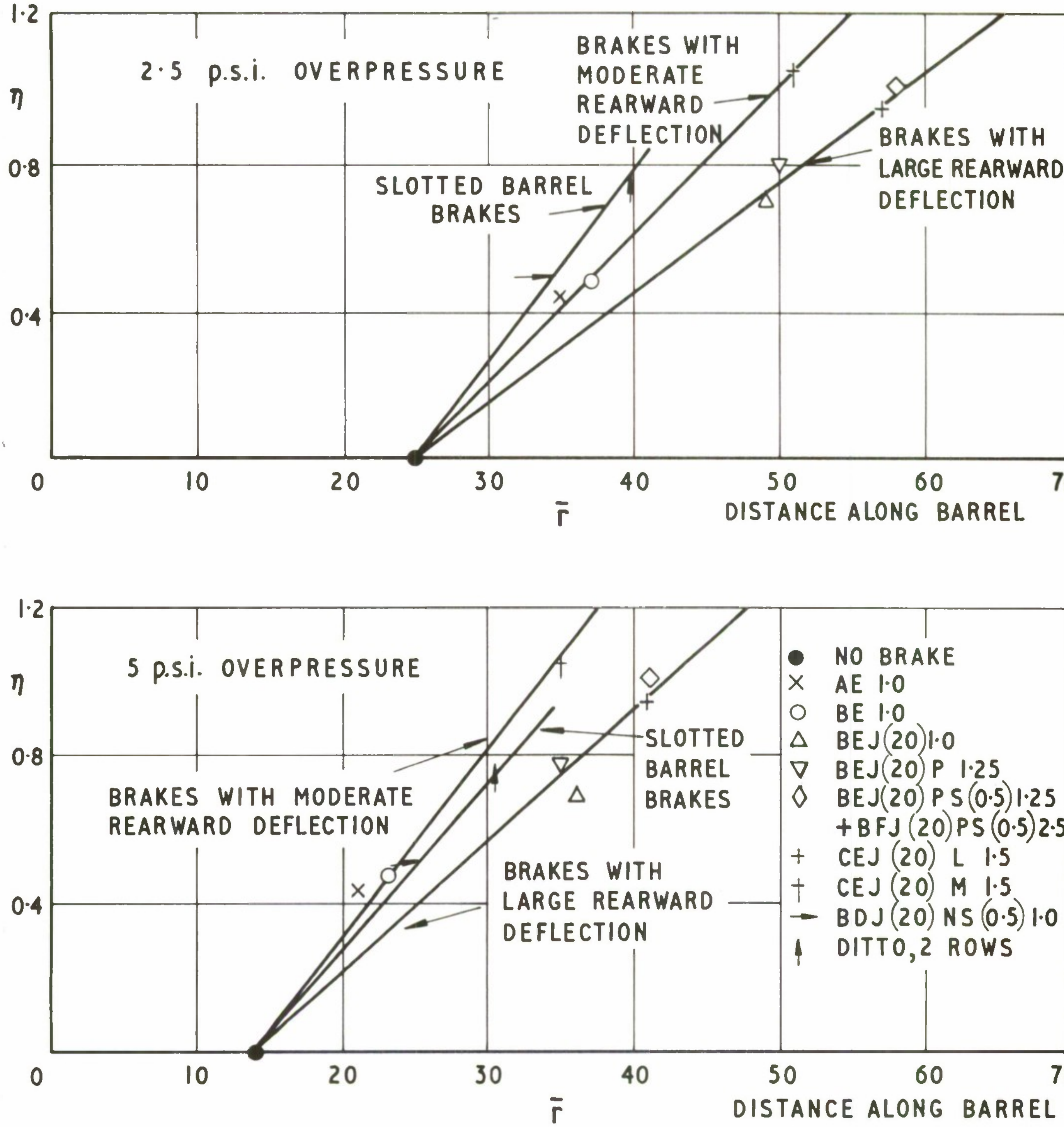


FIG. 15 RELATION BETWEEN AERODYNAMIC INDEX AND OVERPRESSURE ALONG BARREL

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FIG. 1

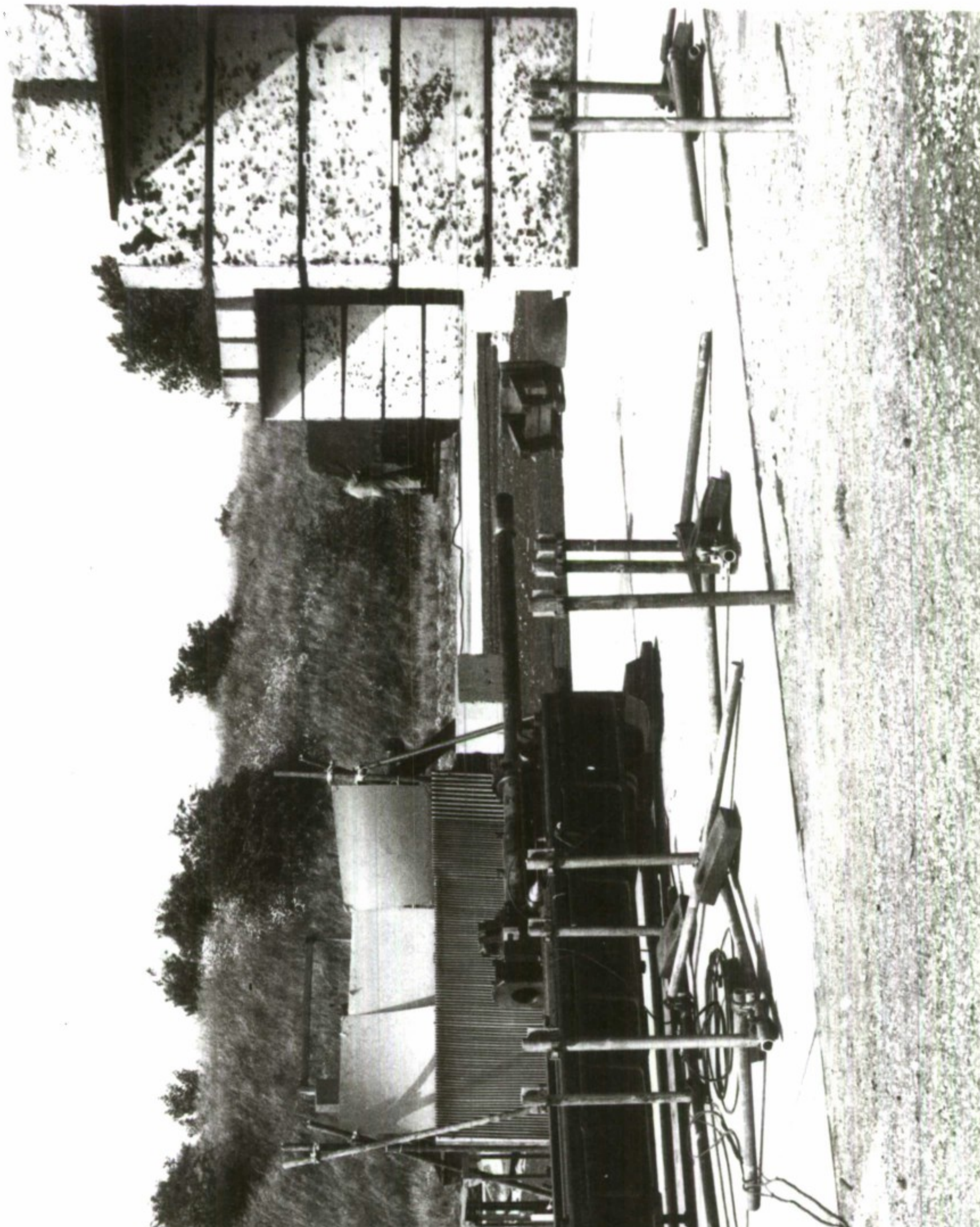

FIG. 1 RARDE FREE-RECOIL MOUNTING

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FIG. 2

FIG. 2 CLOSE-UP OF GUN IN MOUNTING

FIG. 3(a)

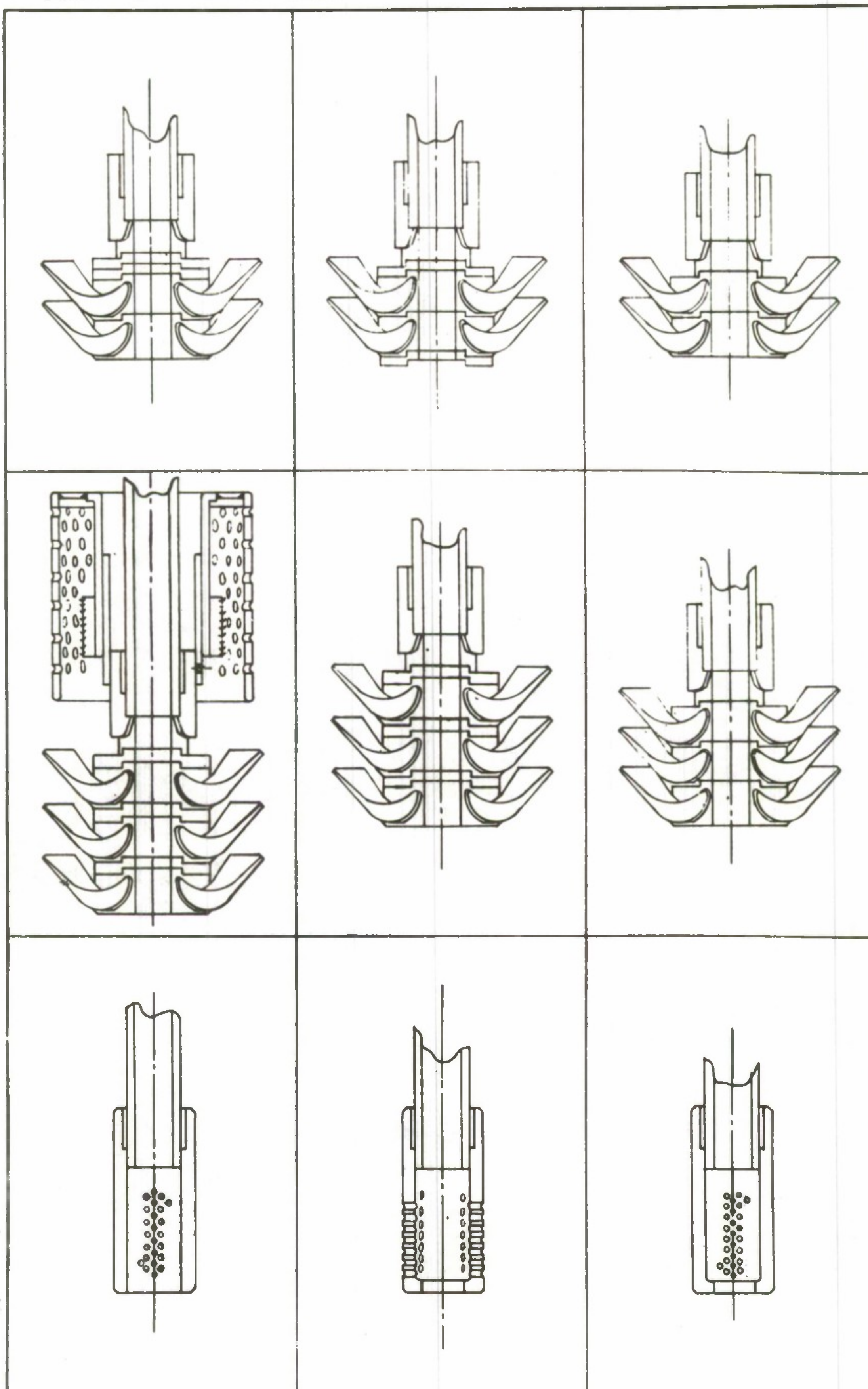

FIG. 3(a) EXPERIMENTAL MUZZLE BRAKES

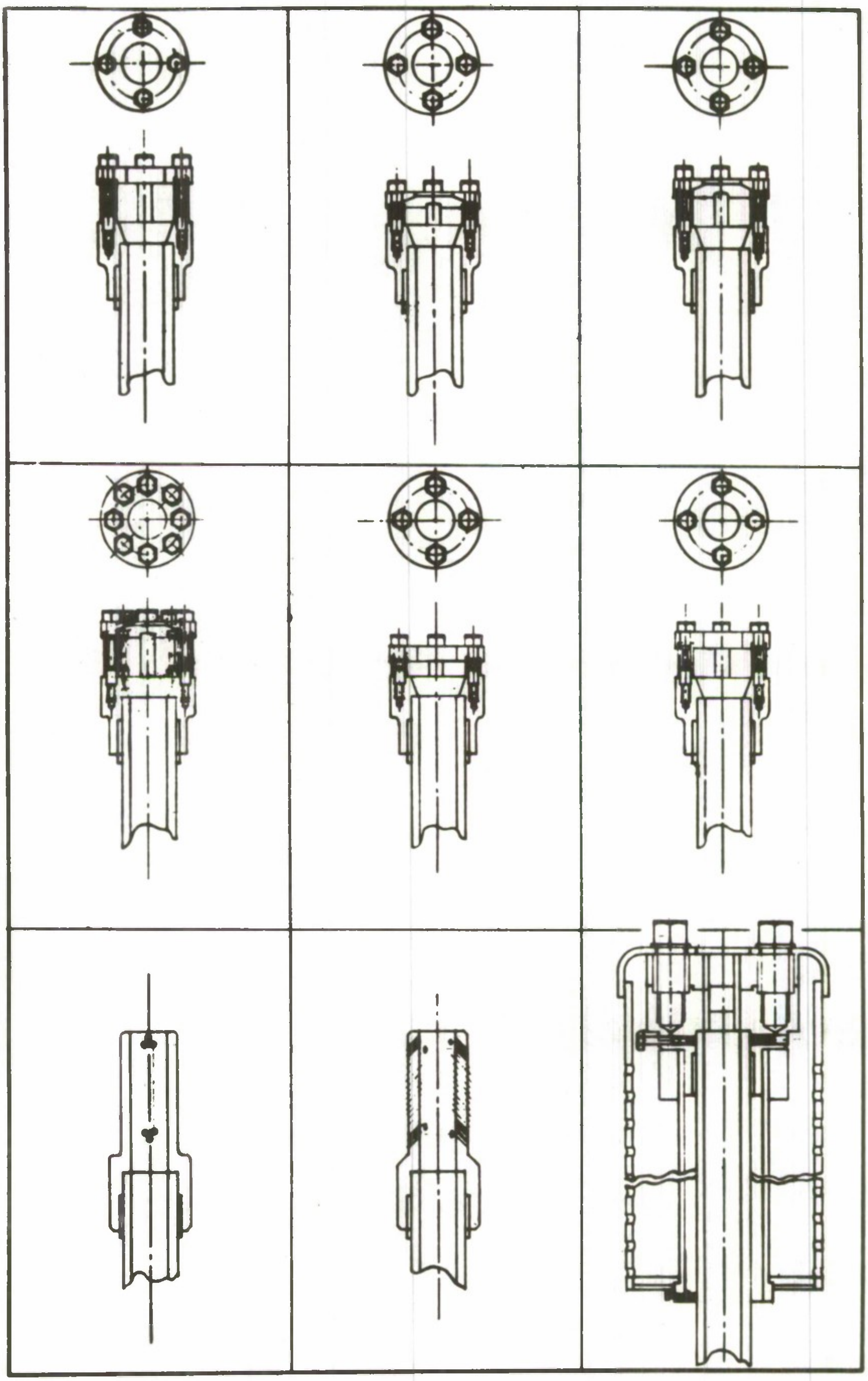

FIG. 3(b) EXPERIMENTAL MUZZLE BRAKES

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FIG. 4(a)

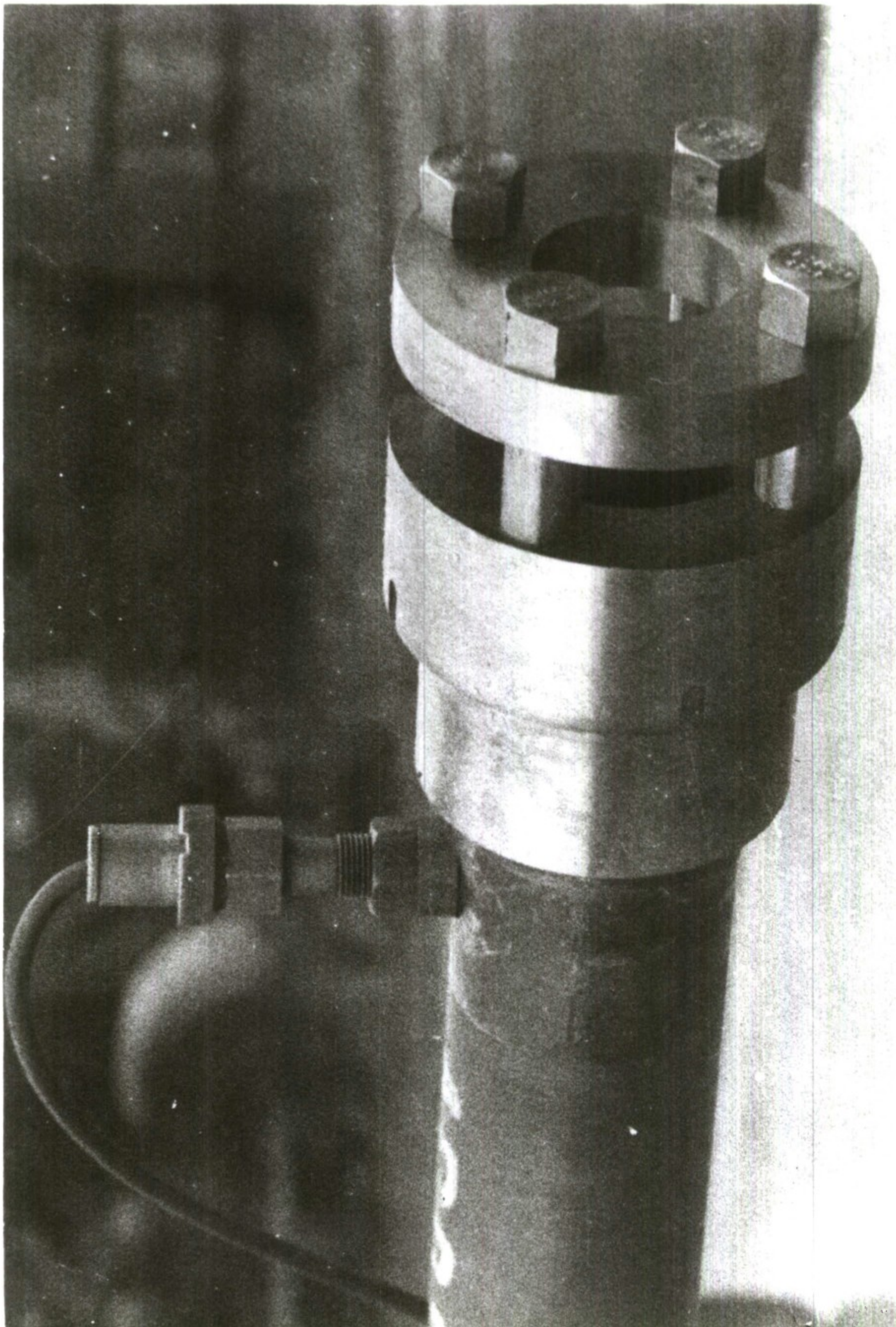

FIG. 4(a) FULL CALIBRE VERSION OF MODEL BRAKE

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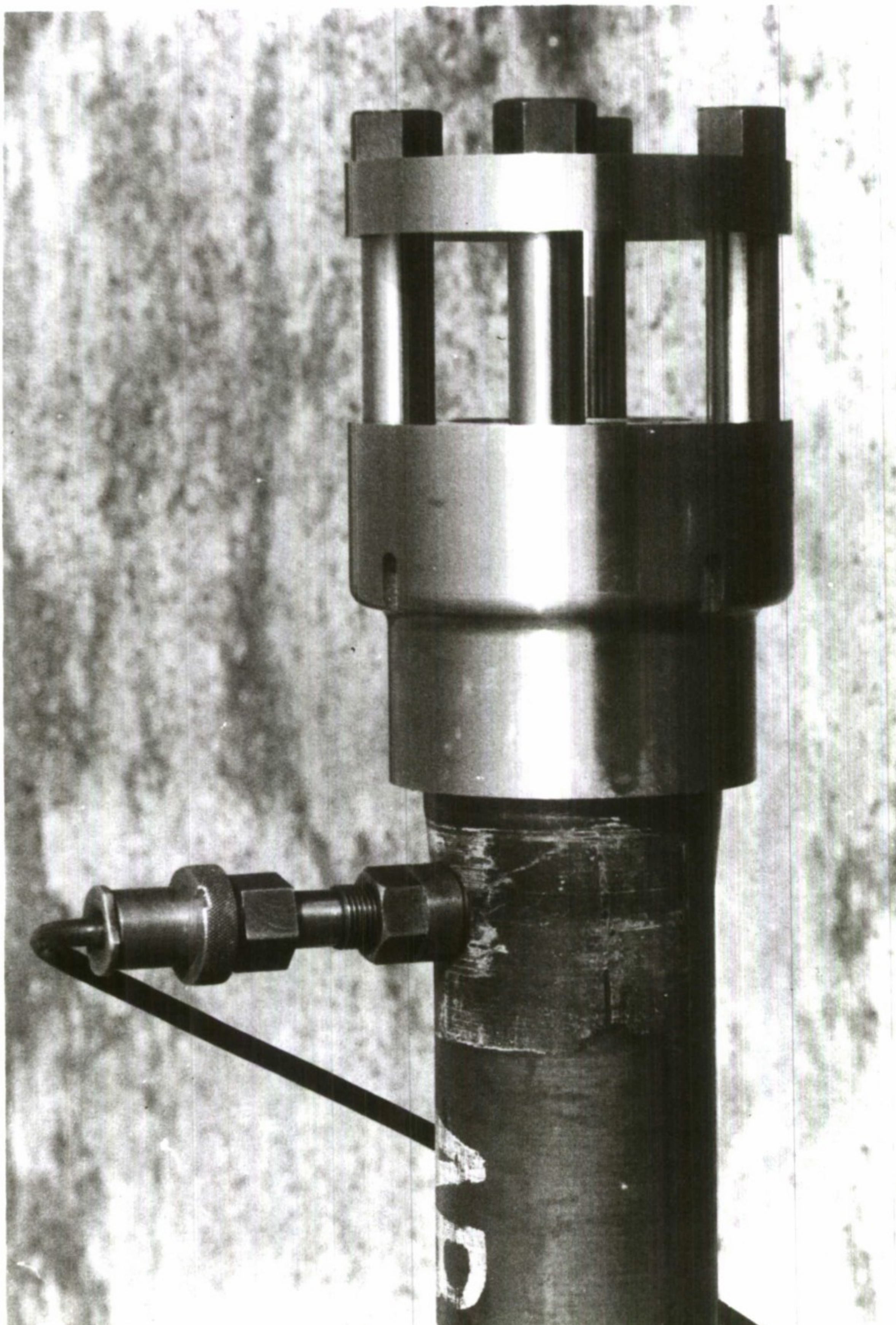

FIG. 4 (b) FULL CALIBRE VERSION OF MODEL BRAKE

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FIG. 5

FIG. 5 EXPERIMENTAL BLAST DIFFUSER

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 FIG. 6

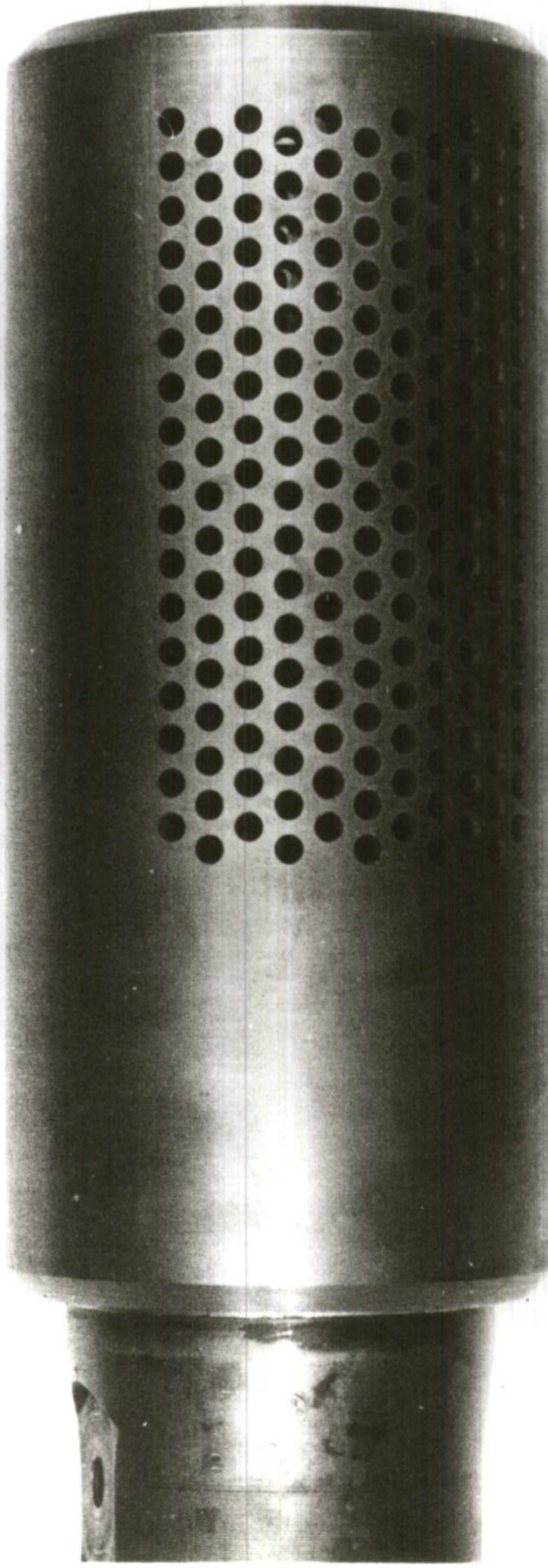

FIG. 6 "PEPPERPOT" MUZZLE BRAKE

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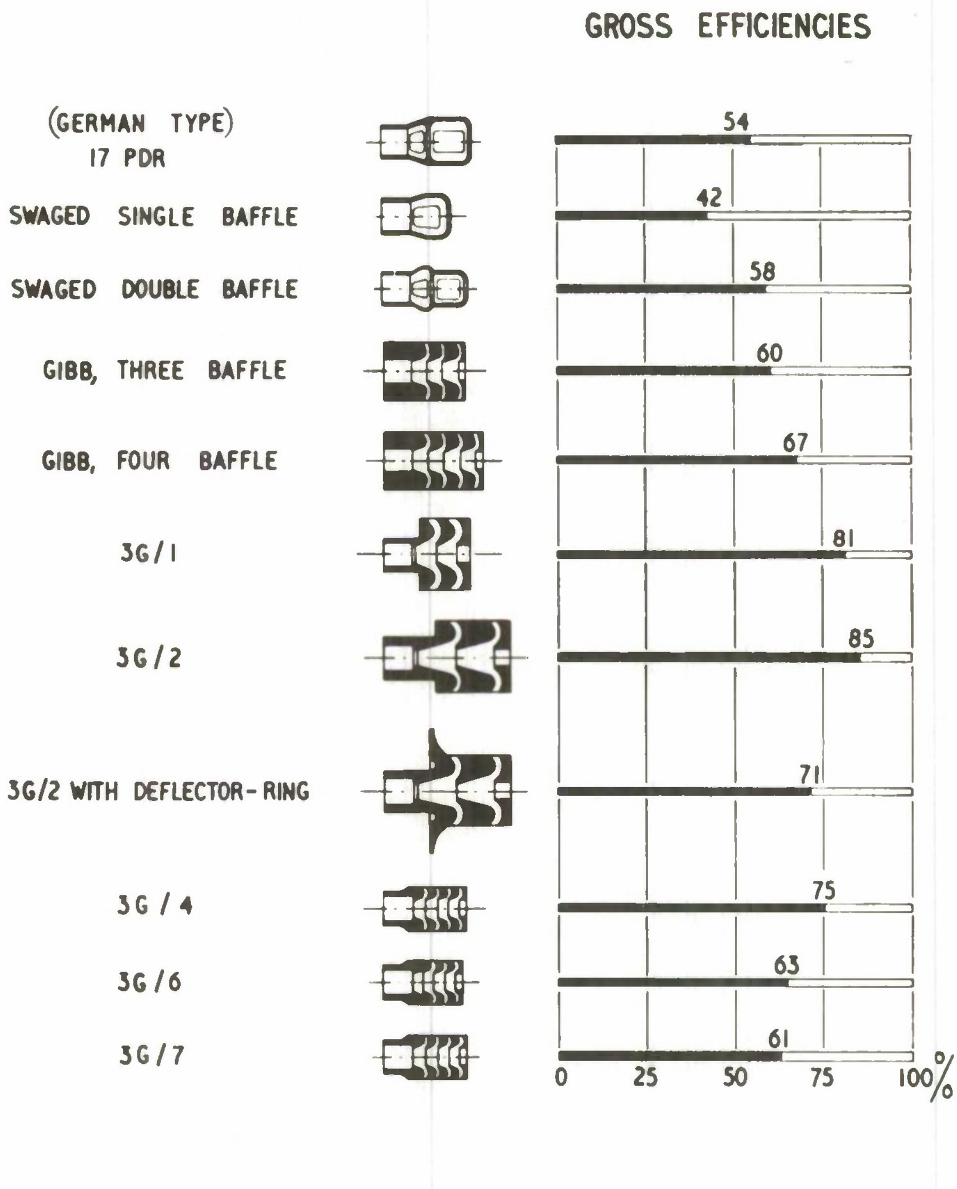
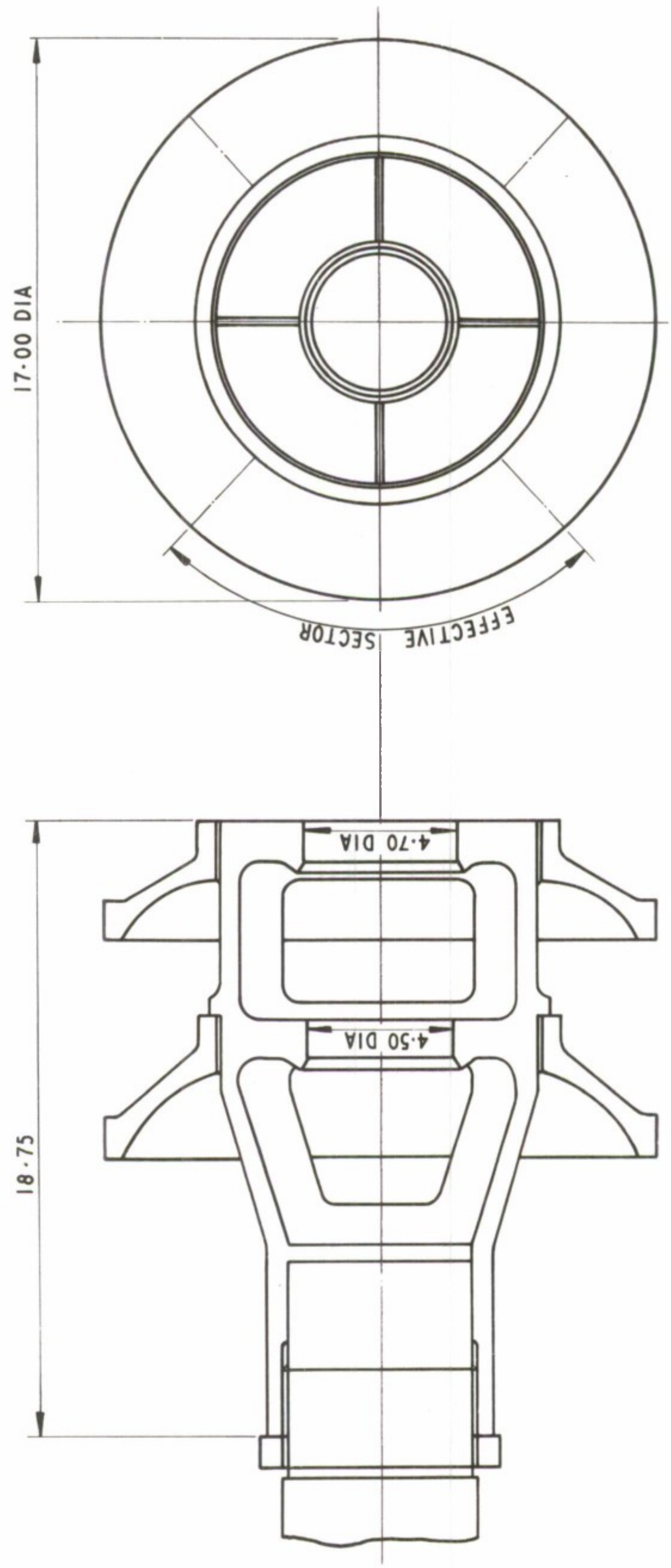


FIG.1 TYPICAL BRITISH MUZZLE BRAKES OF WORLD WAR II PERIOD



INTRINSIC EFFICIENCY	MOMENTUM INDEX	AERODYNAMIC INDEX	FITTED TO
58	1·84	1·36	L 13 A1 (105 mm ABBOT)
88	2·94	1·38	L 7 A1 (105 mm TANK)

FIG. 2(a) 105 mm UMBRELLA BRAKE

FIG. 2(b) 105 mm UMBRELLA BRAKE

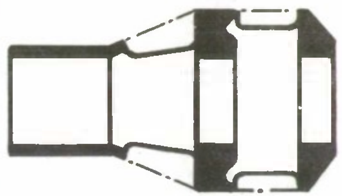
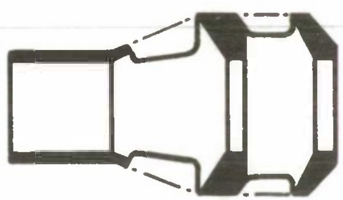
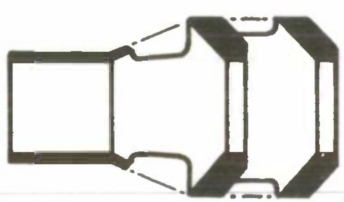
DESIGN	TYPE & DESCRIPTION	CHARGE	INTRINSIC EFFICIENCY	MOMENTUM INDEX	AERODYNAMIC INDEX
	TYPE 'A' (BI/1512/54) FRONT AND REAR BAFFLES FLAT.	4	31 %	1·51	0·87
		5	34·5 %	1·24	0·85
		SUPER	38·8 %	0·945	0·85
	TYPE 'B' (BI/3760/54) FRONT BAFFLE ANGLE 63° FROM HORIZONTAL, REAR BAFFLE ANGLE 70° FROM HORIZONTAL	4	32·6 %	1·525	0·93
		5	38·4 %	1·42	0·94
		SUPER	41·6 %	0·993	0·91
	TYPE 'C' (BI/5028/54) FRONT AND REAR BAFFLE ANGLES 50° FROM HORIZONTAL	4	33 %	1·625	1·08
		5	40·6 %	1·487	1·03
		SUPER	46 %	1·21	1·03

FIG. 3 EXPERIMENTAL BRAKES FOR 105 mm LIGHT GUN

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FIG.4

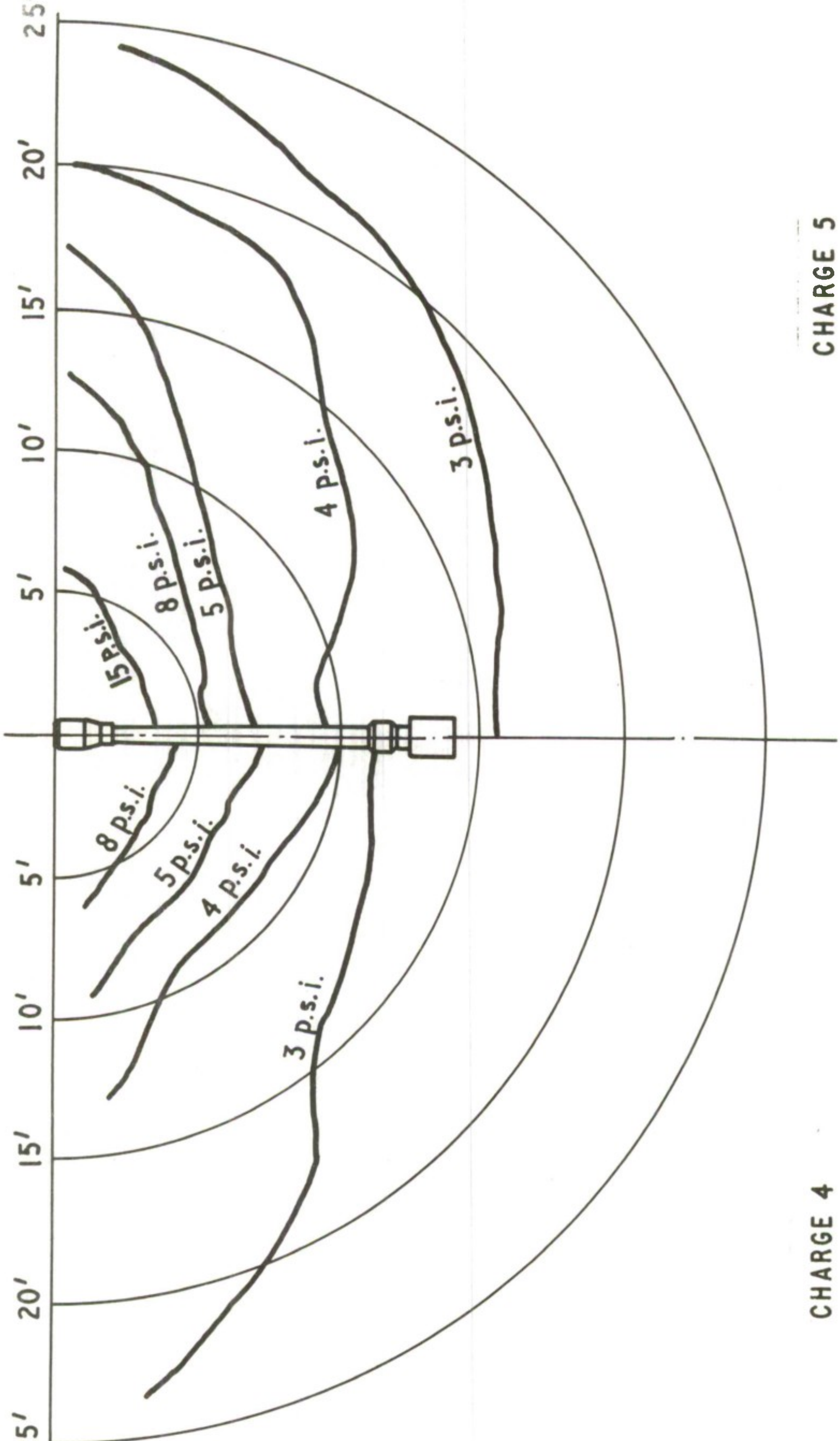

FIG. 4 OVERPRESSURES FOR 105 mm LIGHT GUN BRAKE TYPE A

FIG.5

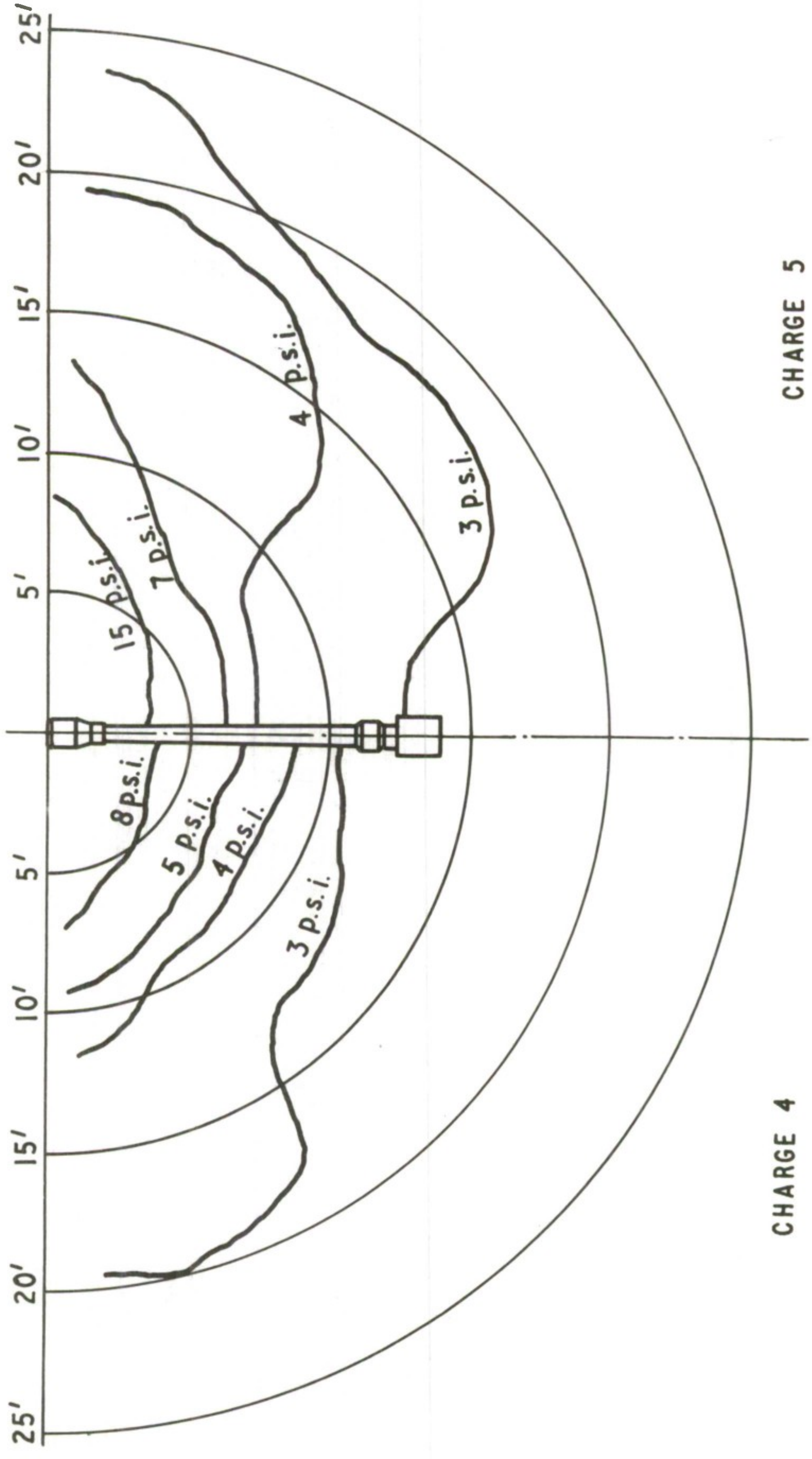

FIG. 5 OVERPRESSURES FOR 105 mm LIGHT GUN BRAKE TYPE B

FIG.6

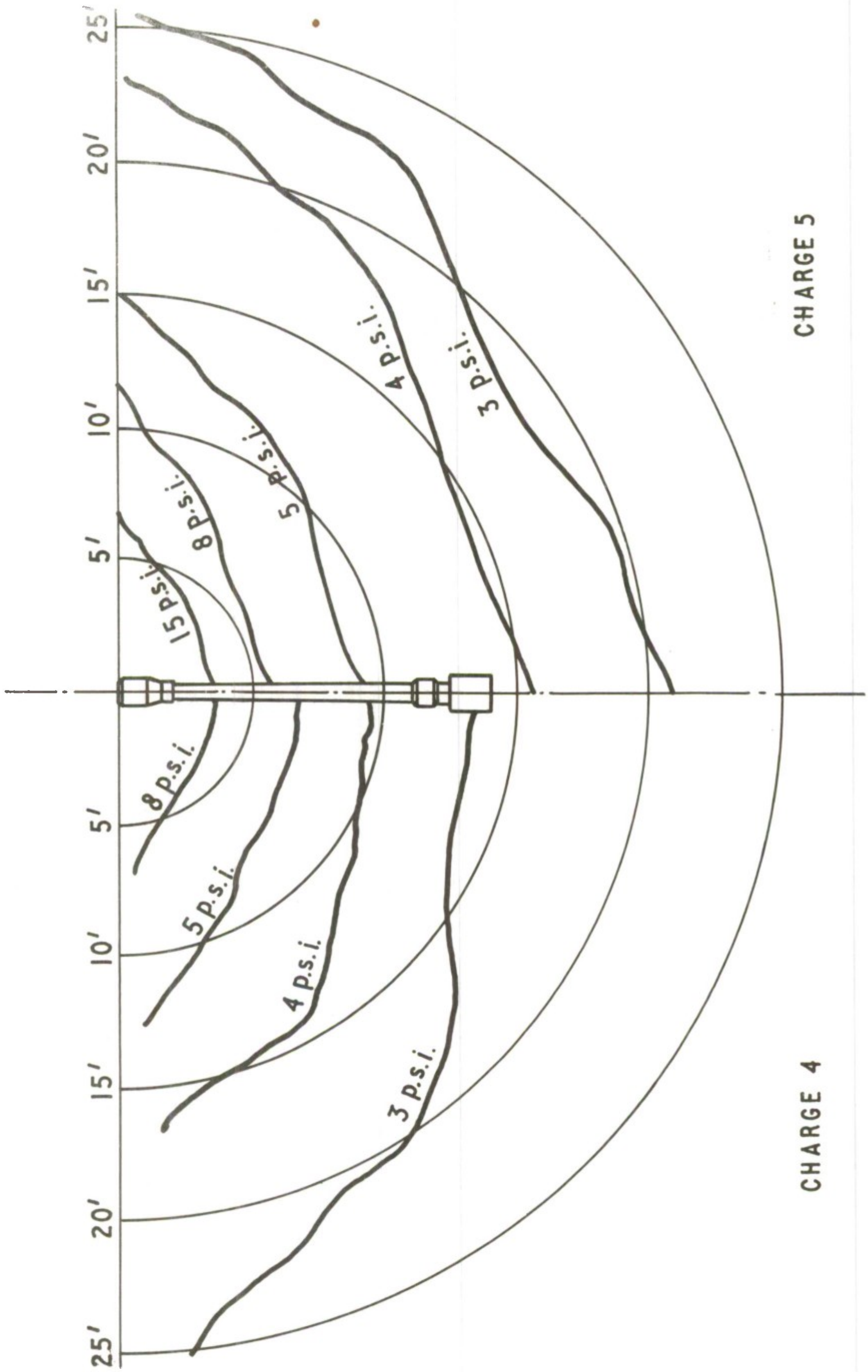

FIG. 6 OVERPRESSURES FOR 105 mm LIGHT GUN BRAKE TYPE C

FIG.7

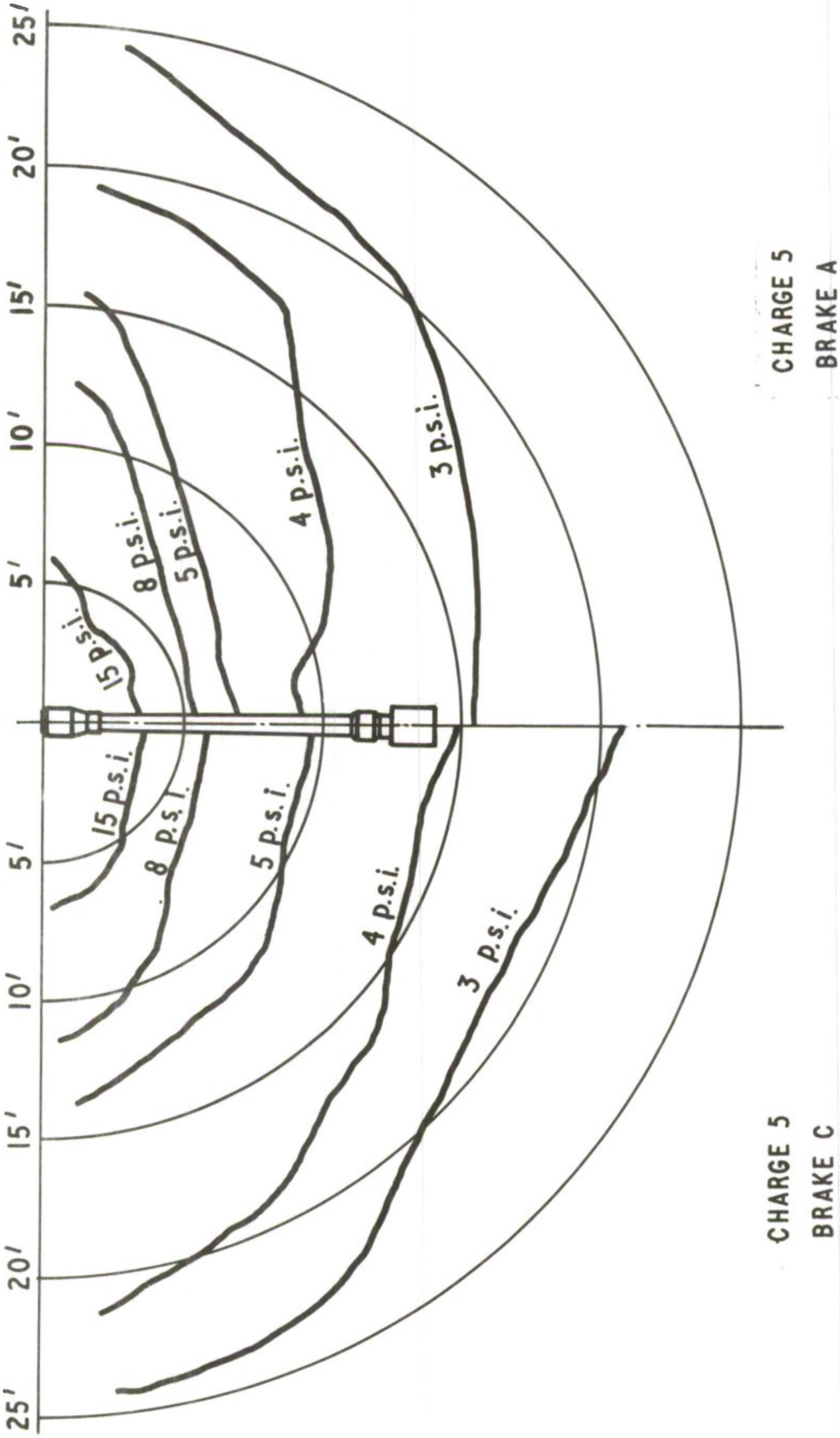

FIG.7 COMPARISON OF OVERPRESSURES FOR 105 mm LIGHT GUN BRAKES TYPES A & C

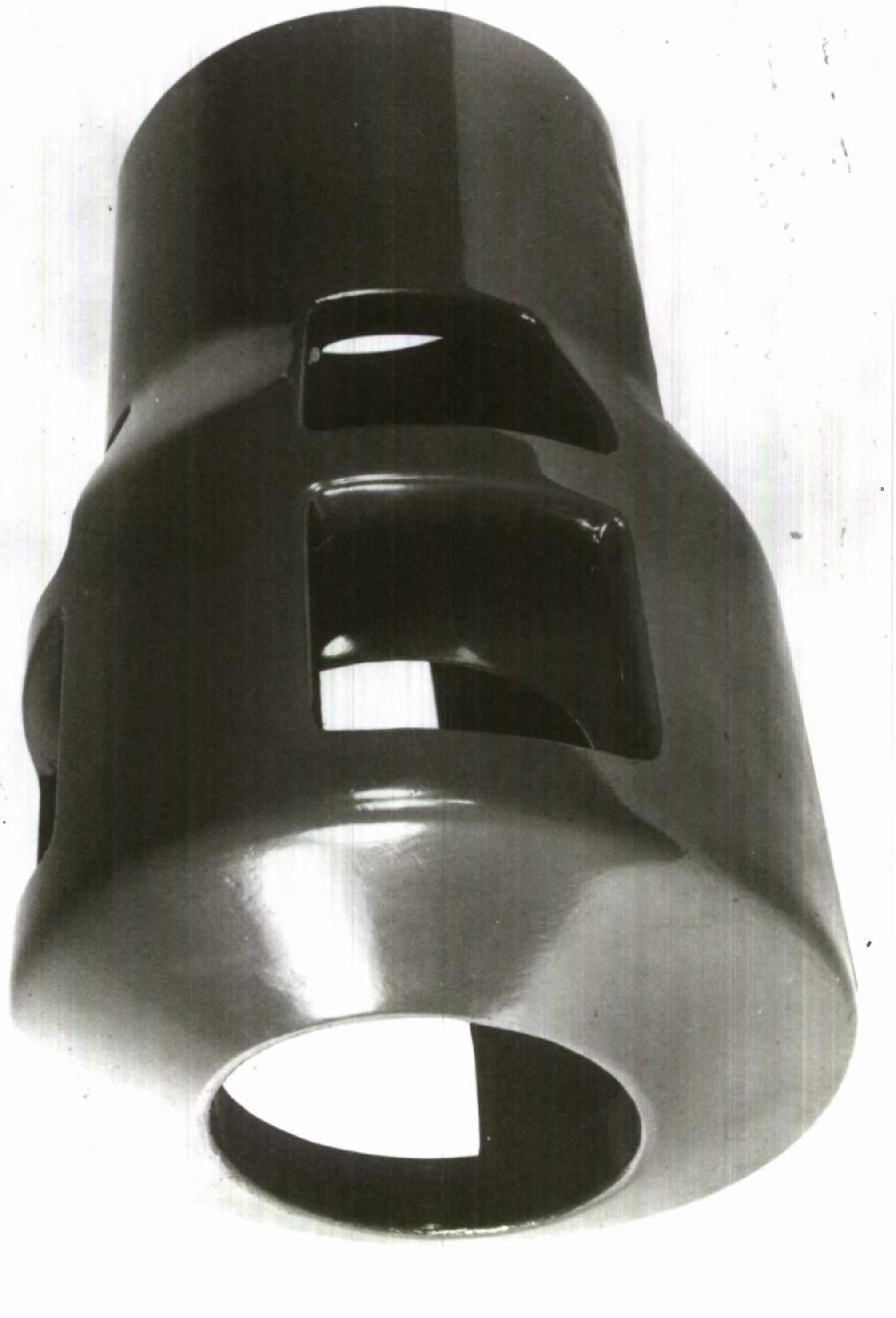

FIG. 8 MODERN MUZZLE BRAKE WITH ALL-ROUND VENTING

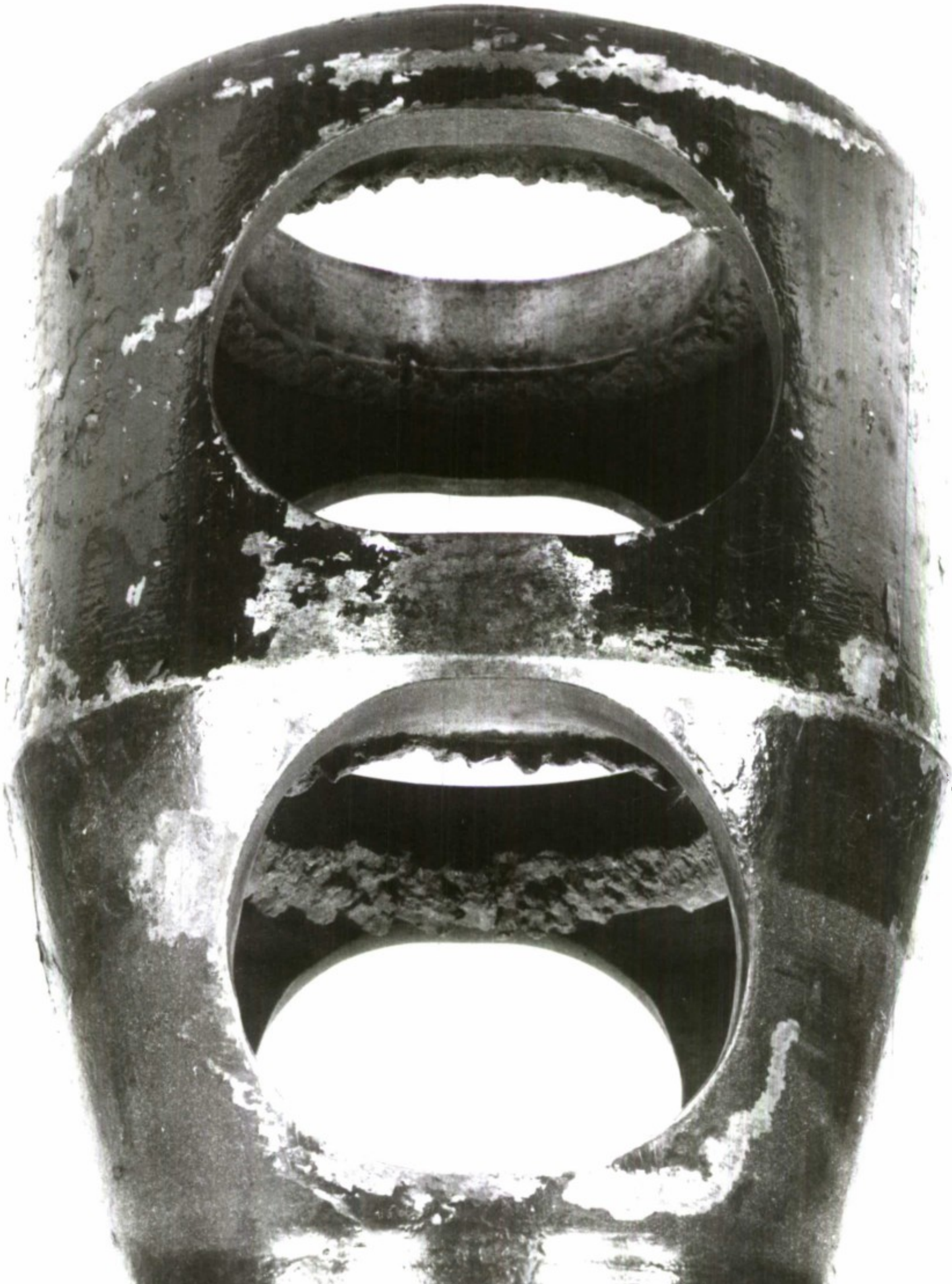

FIG. 9 DAMAGE TO BRAKE BY DISCARDING DRIVING BAND

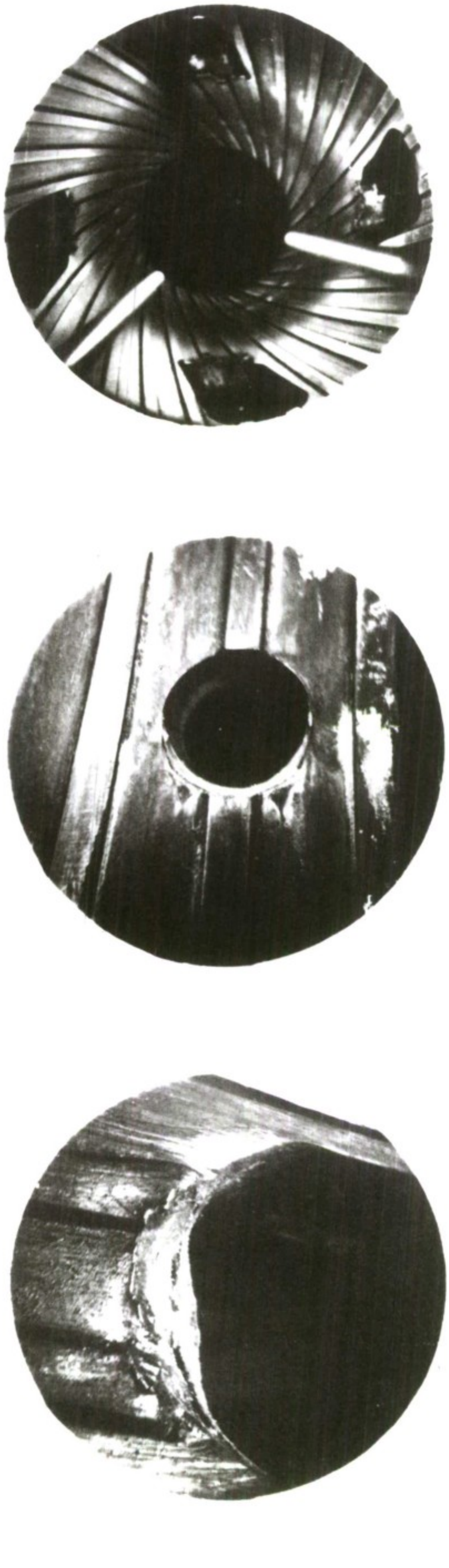

FIG.10 INTERNAL VIEWS OF PERFORATED BARREL TYPE BRAKE

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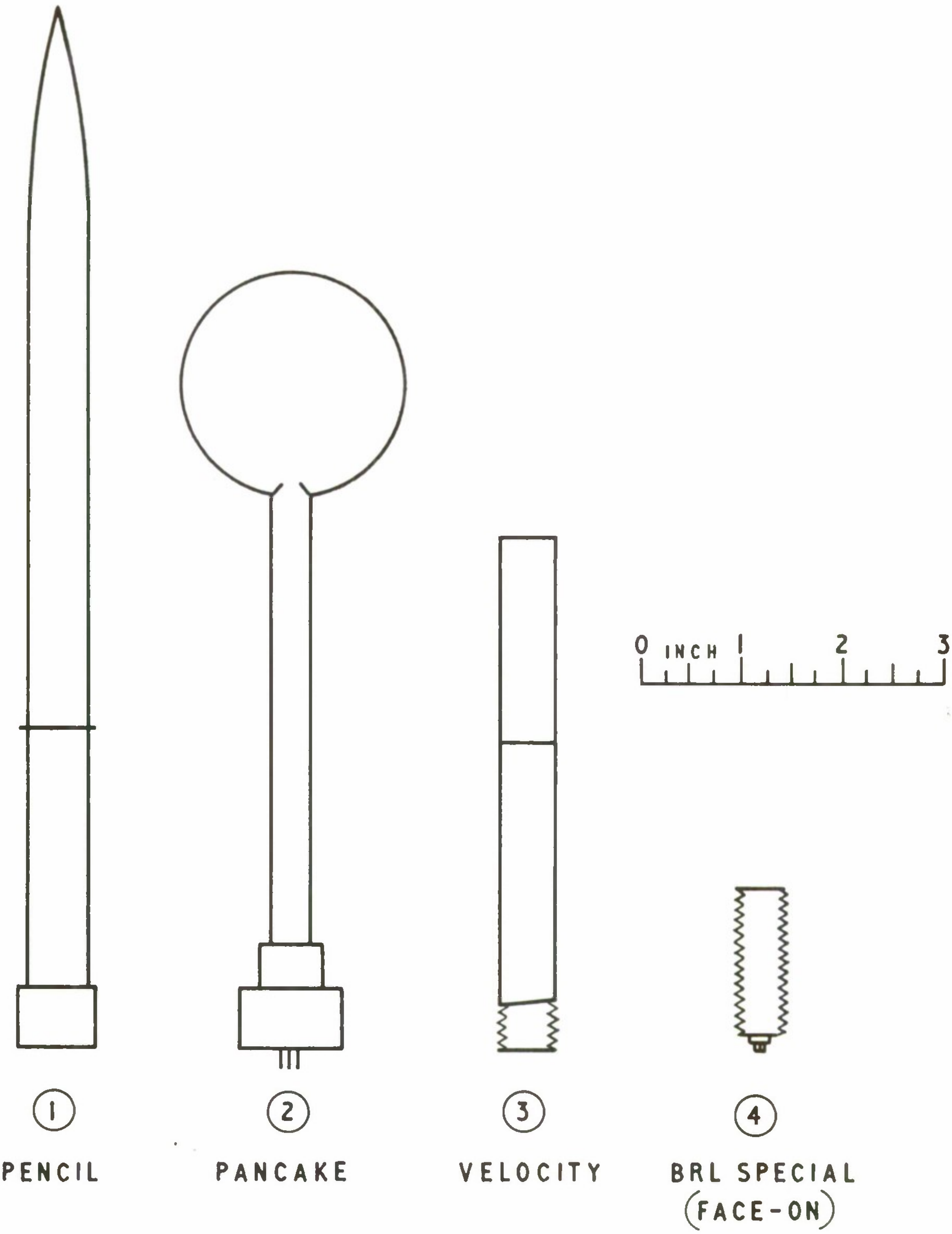
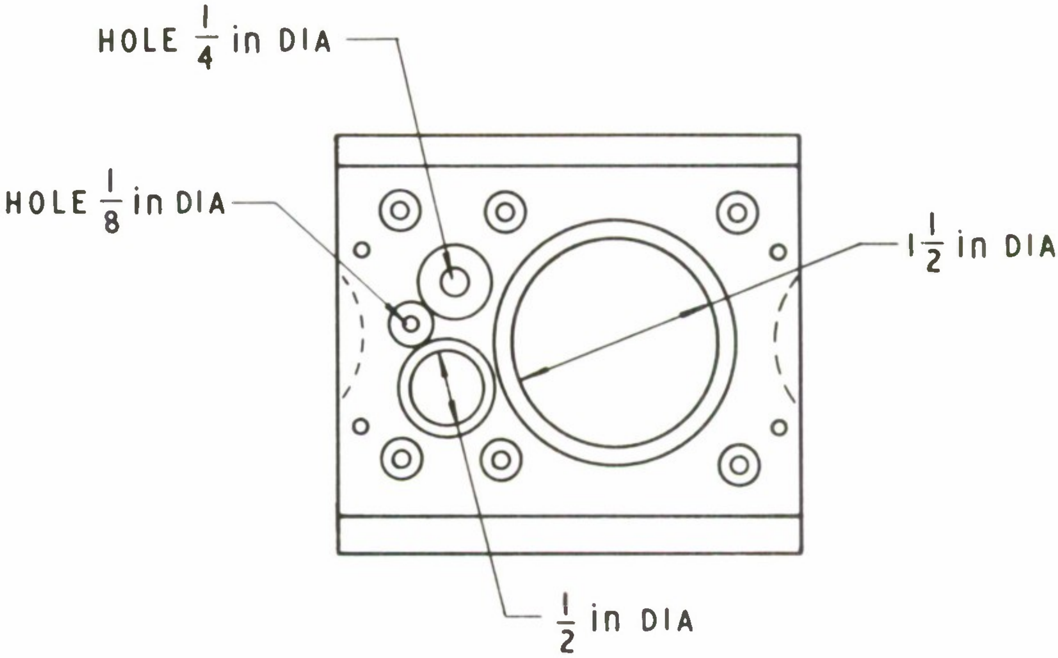
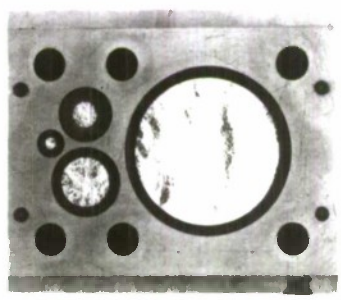


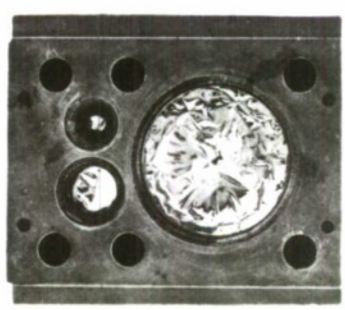
FIG. I BRL BLAST GAUGES



MODIFIED ADAMS BLAST GAUGE



BEFORE



AFTER

FIG. 2 FOIL GAUGE

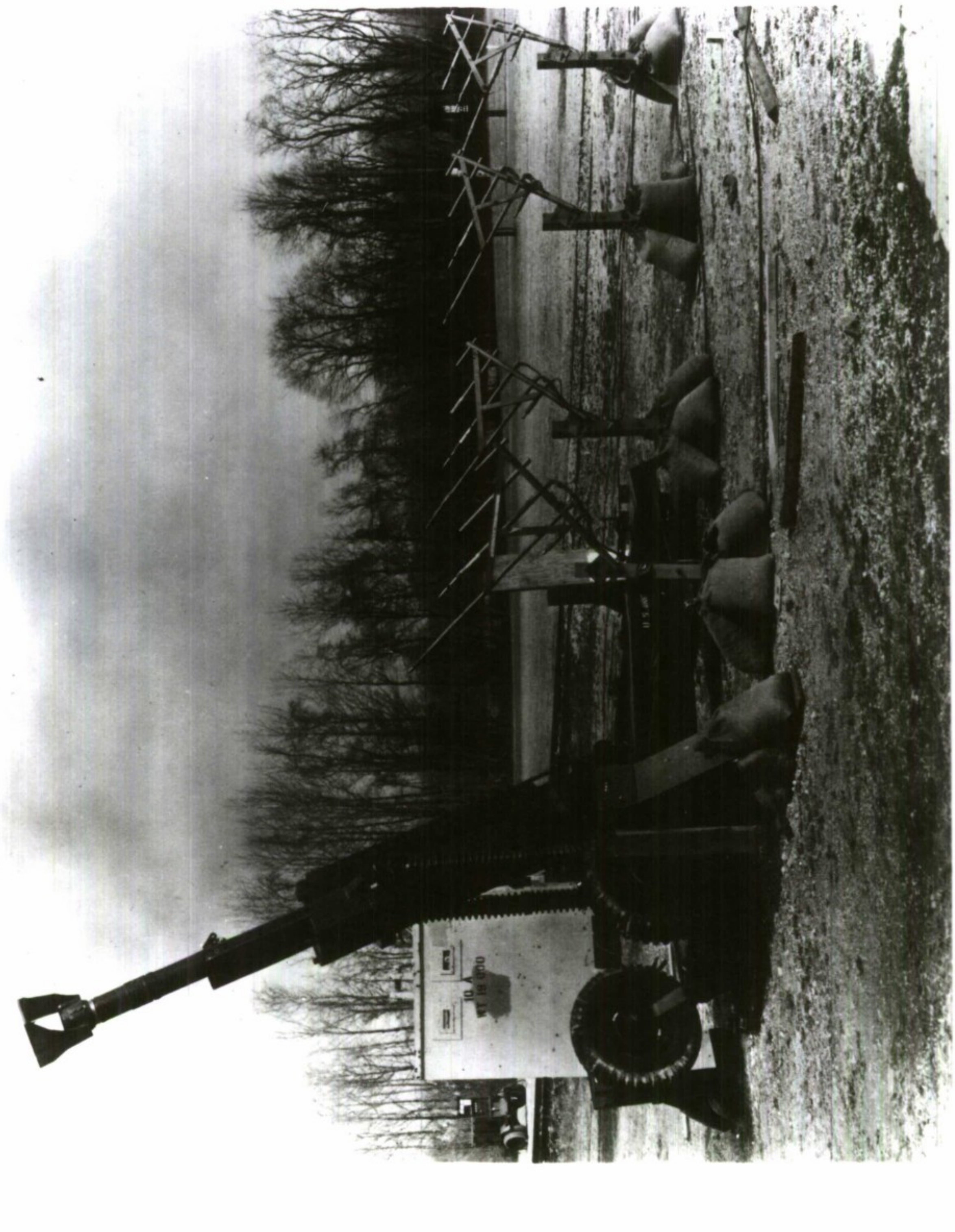


FIG. 3 PENCIL GAUGES AROUND 105mm HOWITZER M102

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FIG. 4

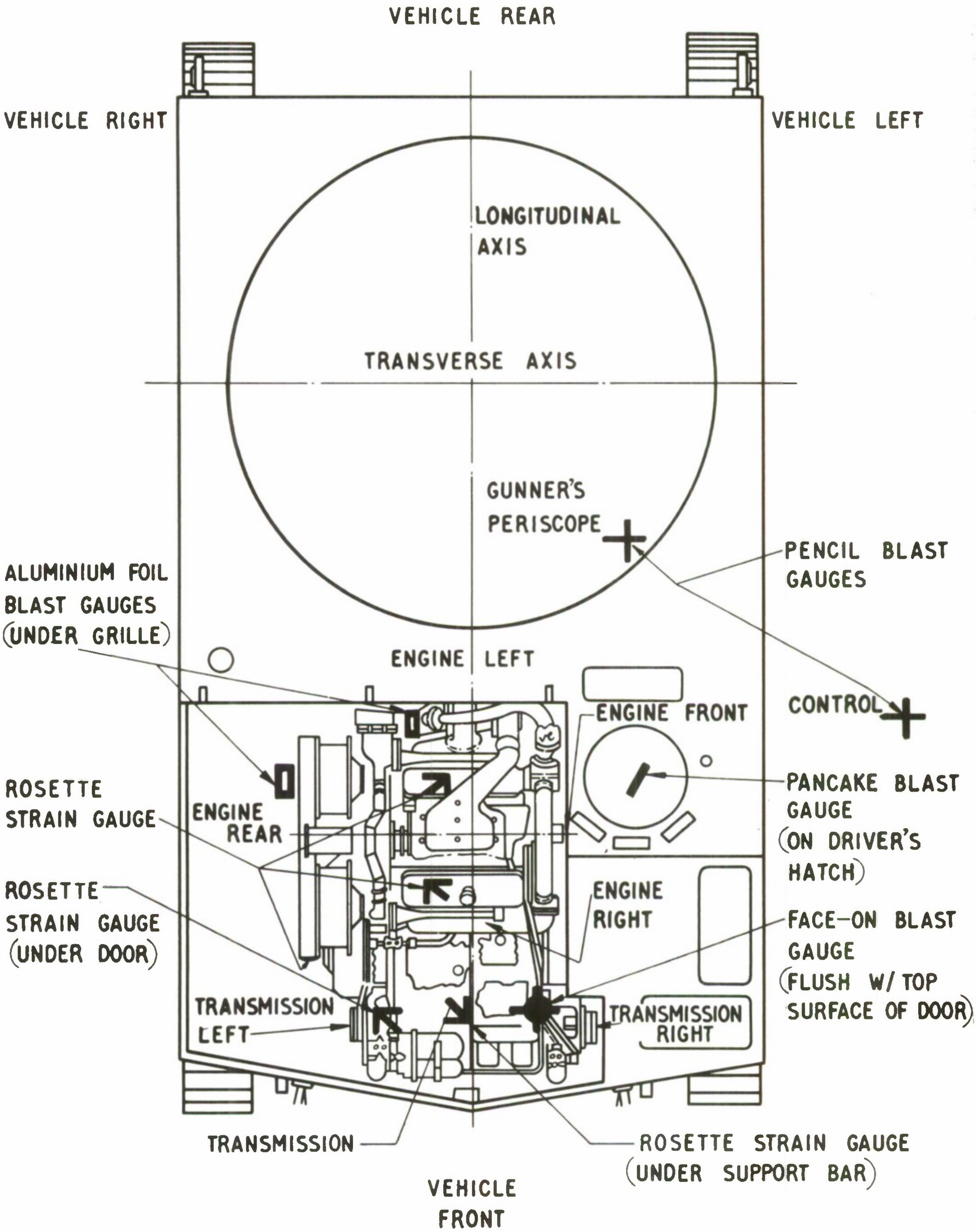

FIG. 4 LOCATION AND ORIENTATION OF GAUGES

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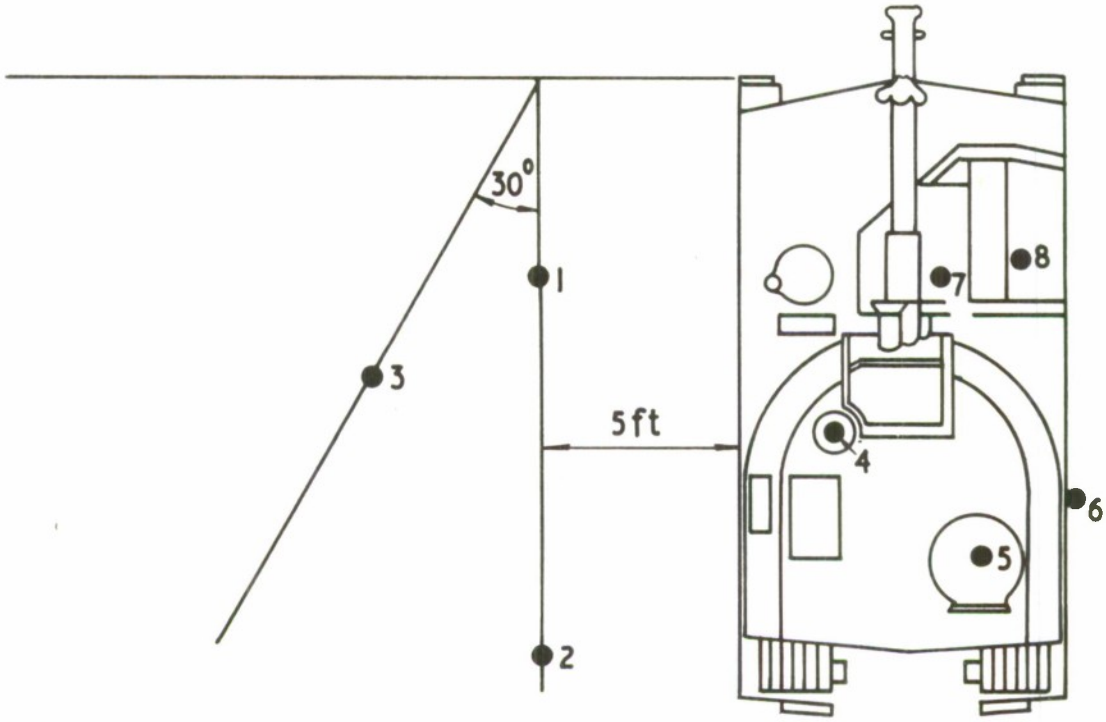

POSITION NUMBER

1 — 12·7 ft FROM FRONT FACE OF MUZZLE BRAKE WITH HOWITZER AT 0°
2 — 20·0 ft FROM FRONT FACE OF MUZZLE BRAKE WITH HOWITZER AT 0°
3 — 23·8 ft FROM FRONT FACE OF MUZZLE BRAKE WITH HOWITZER AT 0°
4 — PANORAMIC TELESCOPE (GUNNERS EAR LEVEL)
5 — COMMANDERS HATCH (6in ABOVE TOP OF TURRET)
6 — SIDE DOOR (RIGHT)
7 — BELOW ENGINE COMPARTMENT GRILLE
8 — BELOW EXHAUST GRILLE

NOTE :- PENCIL-TYPE GAUGES USED AT ALL LOCATIONS

FIG. 5 LOCATION OF BLAST GAUGES FOR COMPARISON OF US & FRG MUZZLE BRAKES, 155 mm HSP M109

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FIG. 6

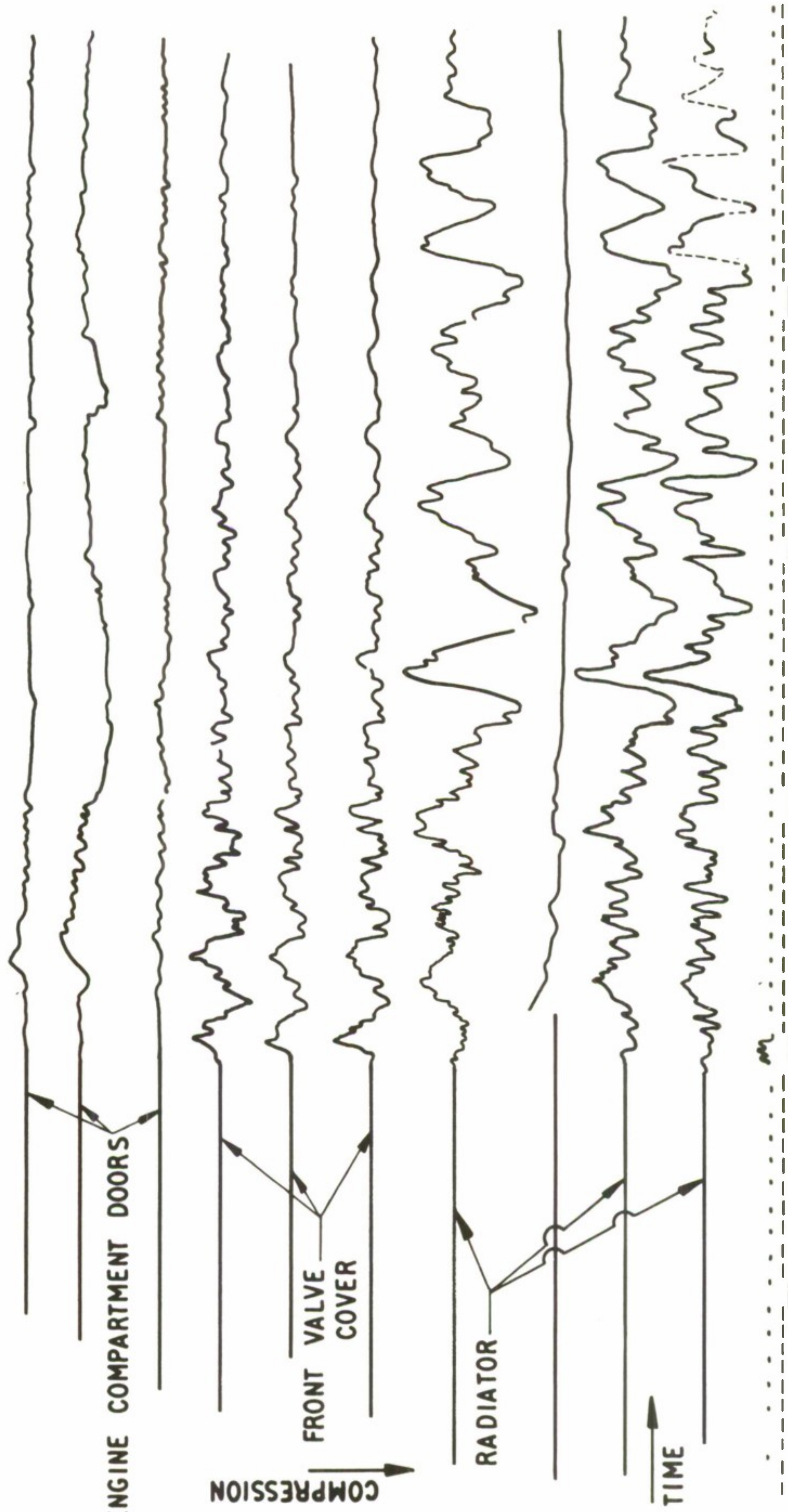

FIG. 6 TYPICAL RECORDS IN M109 TESTS

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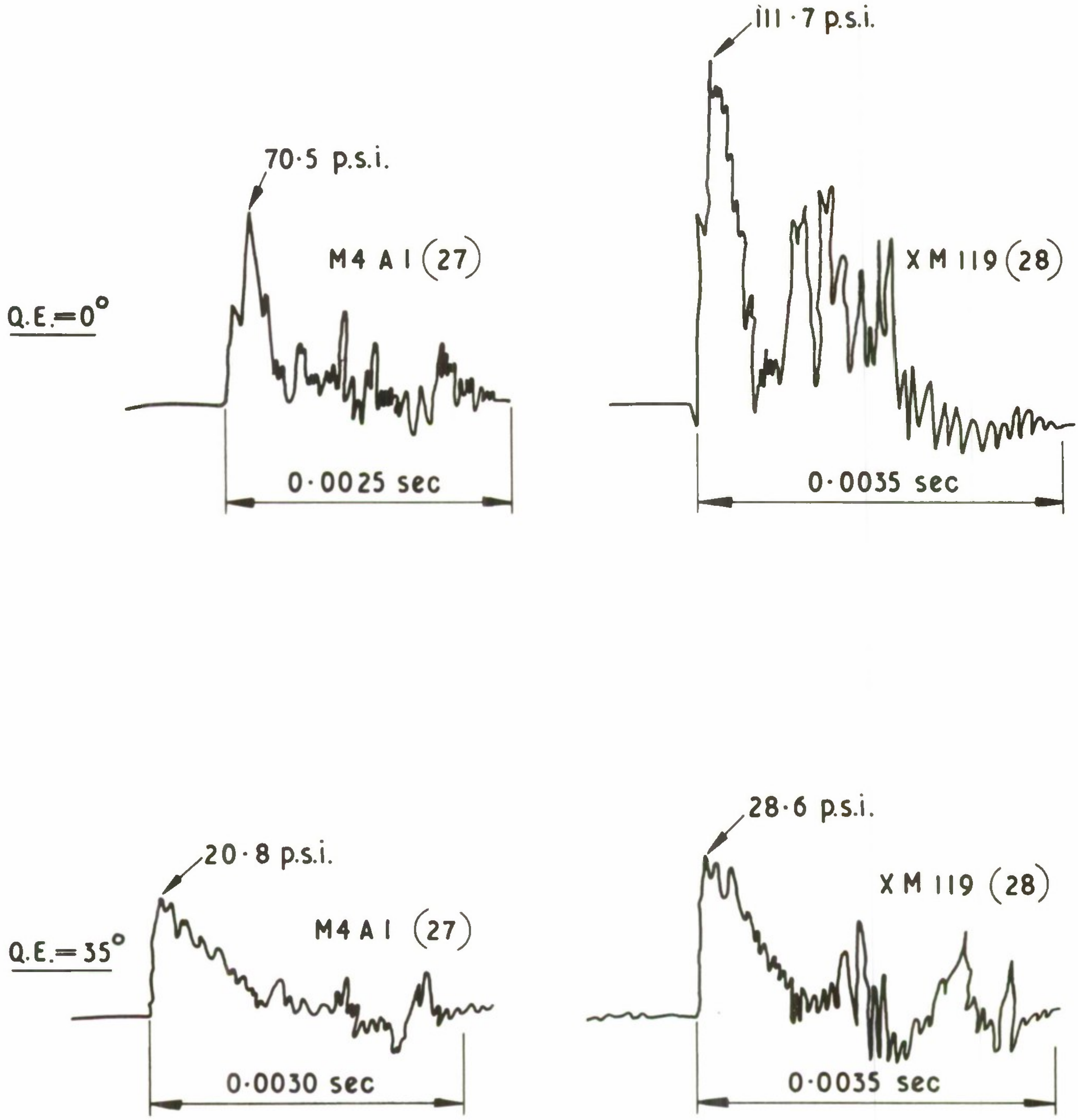

FIG. 7 BLAST PRESSURE RECORDS FOR M4A1 AND XM119 CHARGES

TABLE 1

Overpressure, psi

QE, deg	Charge Zone 7	Charge Zone 8	Change, %
Control gage.			
0	9.5	15.2	+60
35	7.9	12.1	+53
Panoramic telescope aperture.			
0	10.3	16.9	+64
35	8.4	12.9	+53
Driver's hatch.			
0	33.3	45.0	+35
35	16.2	26.4	+63
Engine compartment access door (top).			
0	70.5	111.7	+58
35	22.0	39.9	+81

TABLE 2

Maximum Principal Stresses

QE, deg	Compression, psi Zone 7	Compression, psi Zone 8	Change, %	Tension, psi Zone 7	Tension, psi Zone 8	Change, %
Engine compartment door (underside).						
0	27015	62719	+132	17992	32424	+80
35	5765	10818	+88	11412	15570	+36
Engine compartment door support.						
0	13030	23329	+79	14921	19083	+28
35	10207	15224	+49	9797	13379	+37
Rocker arm assembly cover (front).						
0	12868	63646	+395	25418	35424	+39
35	15008	23357	+56	25071	32858	+31
Rocker arm assembly cover (rear).						
0	66348	82919	+25	75265	68267	-9
35	62201	93003	+50	68336	79340	+16
Radiator tank.						
0	5082	16146	+218	3704	4982	+35
35	6644	8725	+31	4922	7393	+50

Note: A typical strain versus time oscilloscope record is shown in Figure 6.

TABLE 3

Comparison of Muzzle Blast Overpressures (psi)
(US vs FRG Muzzle Brakes, 155mm, HSP, M109)
QE = 0^{o}

Rd. No.	Muzzle Brake	Gunner's Ear Pos.[a]	Command Pos.[a]	Rt. Side Door[b]	Engine Compart[b]	Exhaust Grille[b]	Blast Gage Position[a] No. 1[c]	No. 2[c]	No. 3[c]
Charge: M4A1, Lot No. BAJ 37436									
1	FRG	–	–	–	Lost	–	–	–	–
2		1.05	2.73	2.97	9.59	11.92	6.63	1.75	2.74
3		.96	2.45	2.14	8.85	13.99	6.98	1.58/1.69	2.96
Avg		1.00	2.59	2.57	9.22	12.95	6.80	1.66/1.69	2.85
7	US	1.48	3.86	3.91	23.75	20.61	7.68	2.01	2.85
8		1.39	3.56	3.26	18.47	21.76	8.37	1.90	3.26
9		1.48	3.32	2.97	15.11	21.76	8.02	1.90	3.39
Avg		1.45	3.58	3.39	19.02	21.38	8.02	1.93	3.16
Charge: M119, Lot No. RAD 64645									
4	FRG	1.57	3.32	4.11	15.11	25.32	10.12	2.32/2.64	3.92
5		1.39	3.40	4.11	15.11	30.23	10.47	2.01/2.43	3.92
6		1.39	3.56	4.40	15.11	20.23	10.82	2.32/2.96	4.48
Avg		1.45	3.43	4.20	15.11	28.55	10.47	2.22/2.68	4.11
10	US	1.83	5.74	6.85	19.31	32.77	12.21	2.53/2.85	4.75
11		1.83	5.52	6.48	18.47	31.49	12.21	2.43/2.74	4.75
12		1.92	4.98	6.50	21.93	34.09	11.86	2.43/3.06	4.75
Avg		1.86	5.41	6.59	19.87	32.74	12.08	2.46/2.88	4.75

Note: Pencil-type blast gages used at all positions. This gage measures side-on (P_S) pressure only. Face-on (P_R) pressure were computed by the following relationships: $P_R = P_S$ (2+6 $= P_S/P_O$

[a] P_S (side-on pressure)

[b] P_R (reflected or face-on pressure)

[c] Gage Distances from Muzzle: No.1 – 12.7 ft
No.2 – 23.8 ft
No.3 – 20.0 ft

TABLE 4

Comparison of Muzzle Blast Overpressures (psi)
(US vs FRG Muzzle Brakes, 155mm, HSP, M109)
QE = 70°

Rd. No.	Muzzle Brake	Gunner's[a] Ear Pos.	Command[a] Pos.	Rt. Side[b] Door	Engine[b] Compart	Exhaust[b] Grille	Blast Gage Position[a] No. 1[c]	No. 2[c]	No.3[c]
Charge:	M4A1, Lot No. BAJ 37436								
22	FRG	1.39	3.20	4.40	9.59	8.93	4.32	2.22	2.99
23		1.48	3.56	4.11	8.83	8.93	3.92	2.22	2.99
24		1.48	3.20	4.11	10.36	13.99	4.32	2.32	3.26
Avg		1.45	3.32	4.20	9.59	10.55	4.18	2.25	3.08
13	US	2.09	4.98	5.58	14.28	15.05	5.10	3.06	2.99
14		1.65	5.16	8.64	14.28	16.16	5.10	2.74	2.99
15		2.00	5.16	5.87	14.28	15.05	5.10	2.74	2.99
Avg		1.91	5.09	6.66	14.28	15.43	5.10	2.81	2.99
Charge:	M119, Lot No. RAD 64645								
19	FRG	2.24	4.98	6.48	14.28	12.10/15.05	6.28	3.38	4.62
20		1.40/2.09	4.98	6.17	16.75	12.95/16.16	7.06	3.16	4.62
21		2.44	4.98	5.87	15.11	13.99/16.16	6.28	2.95	4.62
Avg		1.40/2.25	4.98	6.17	15.35	13.05/15.78	6.53	3.16	4.62
16	US	2.96	7.48	7.69	23.72	22.92/25.32	7.06	3.90	4.62
17		2.79	7.48	8.32	22.84	22.60/25.32	7.46	3.90	4.86
18		2.62	7.83	8.64	23.72	21.76/25.32	7.46	3.80	4.62
Avg		2.79	7.60	8.23	23.42	22.43/25.32	7.33	3.87	4.71

Note: Pencil-type blast gages used at all positions. This gage measures side-on (P_S) pressures only. Face-on (P_R) pressure were computed by the following relationships: $P_R = P_S$ (2+6 $= P_S/P_O$

[a]P_S (side-on pressure)

[b]P_R (reflected or face-on pressure)

[c]Gage Distances from Muzzle: No.1 – 12.7 ft
No.2 – 23.8 ft
No.3 – 20.0 ft

Session II
Item 4 Empirical studies on the reduction of muzzle brake blast

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FIG. 1

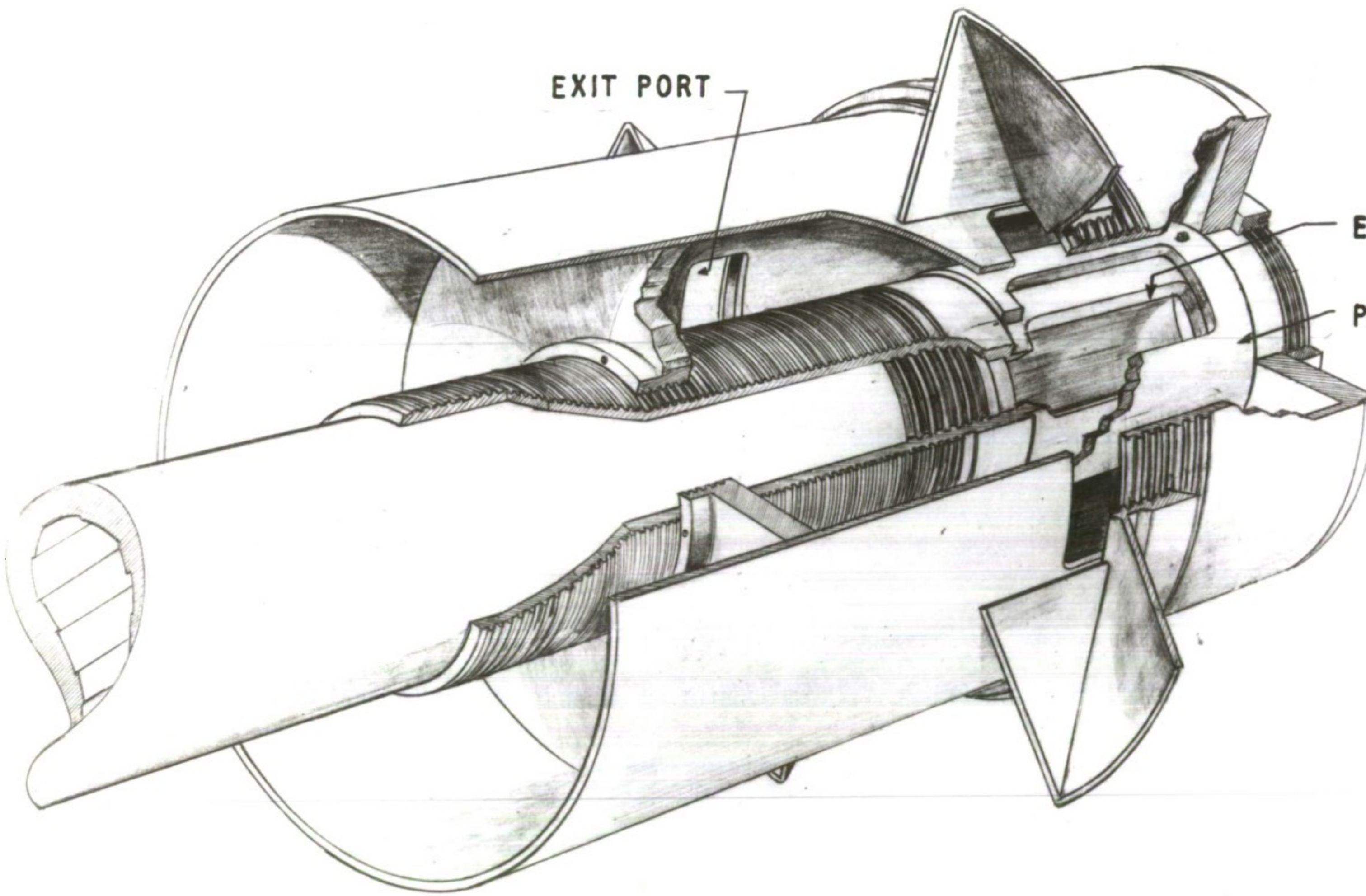

FIG. 1 BRAKE RESERVOIR TEST FIXTURE

FIG.2

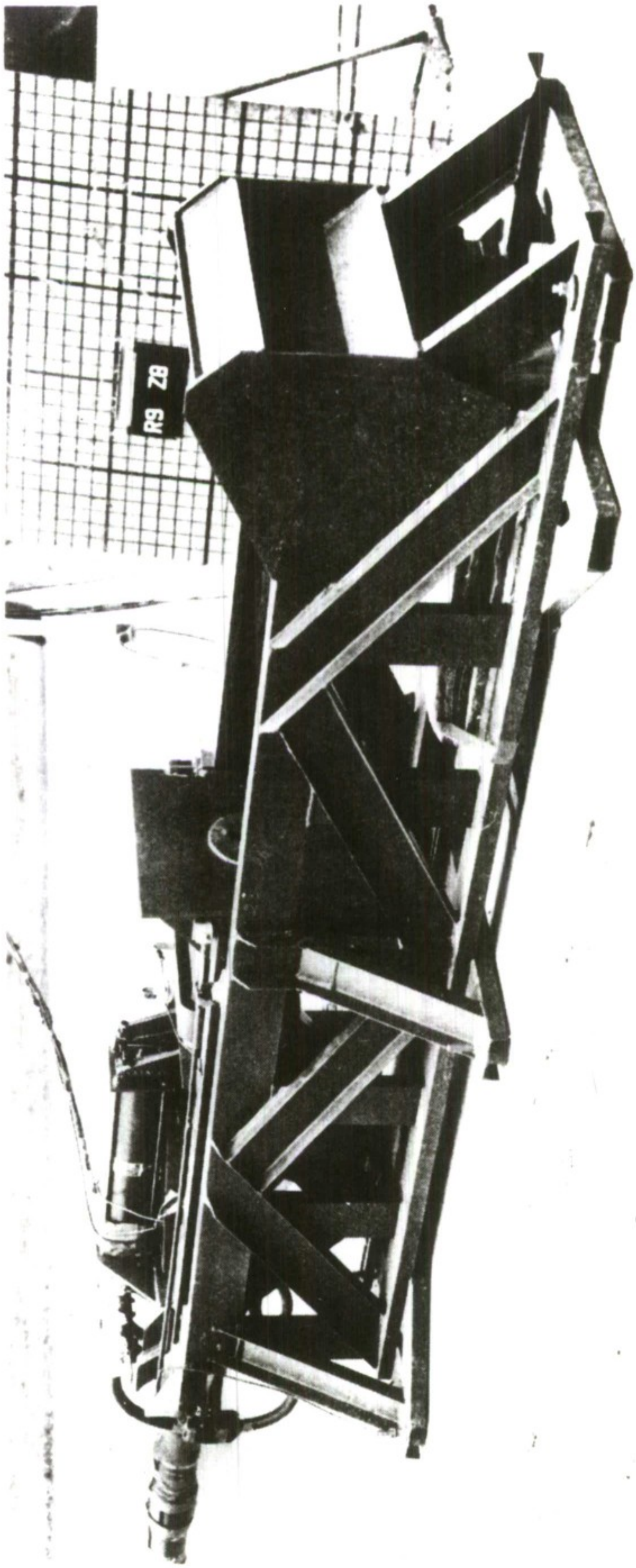

FIG. 2 FREE RECOIL TEST FIXTURE

FIG. 3

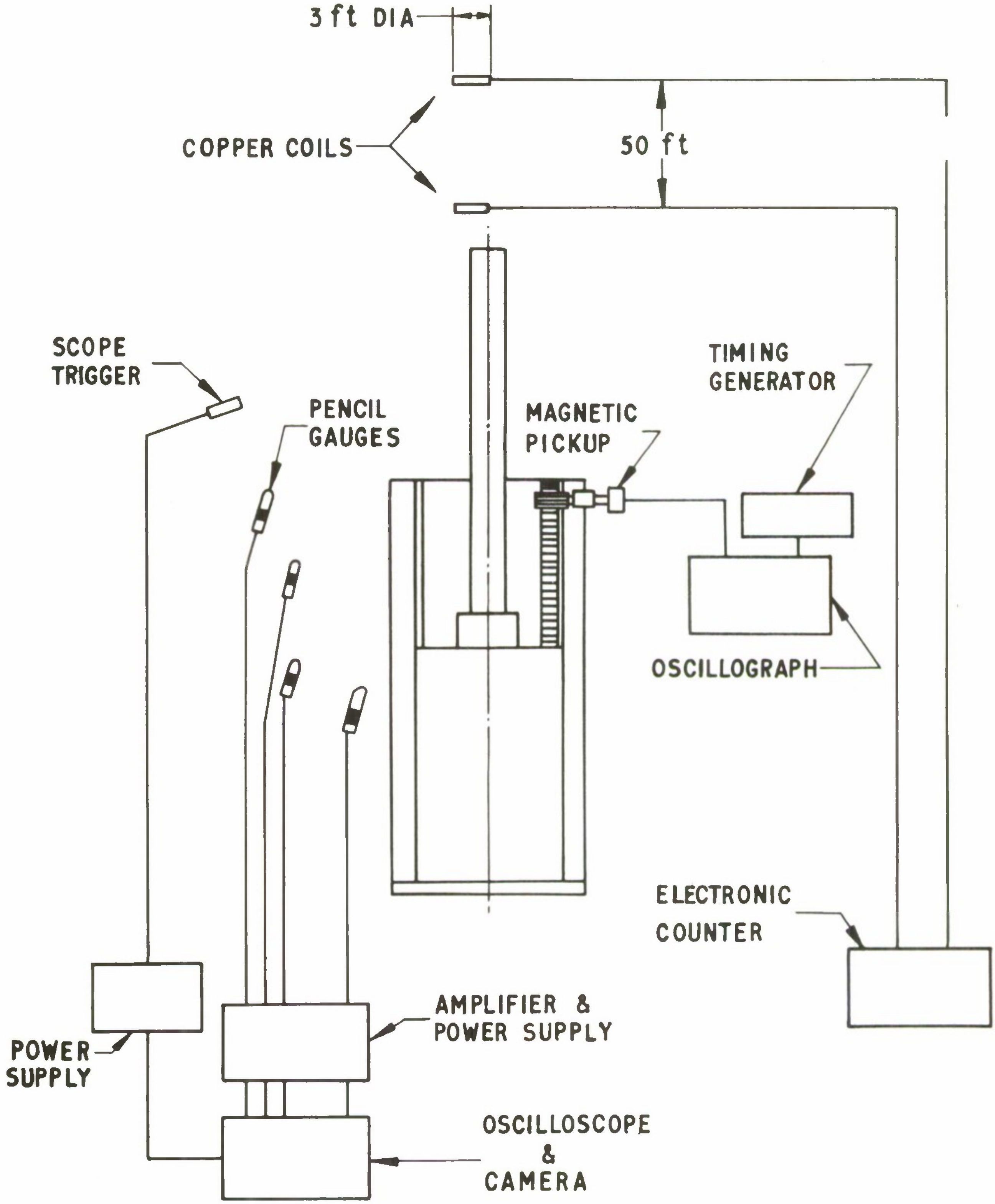

FIG. 3 INSTRUMENTATION LAYOUT

FIG. 4

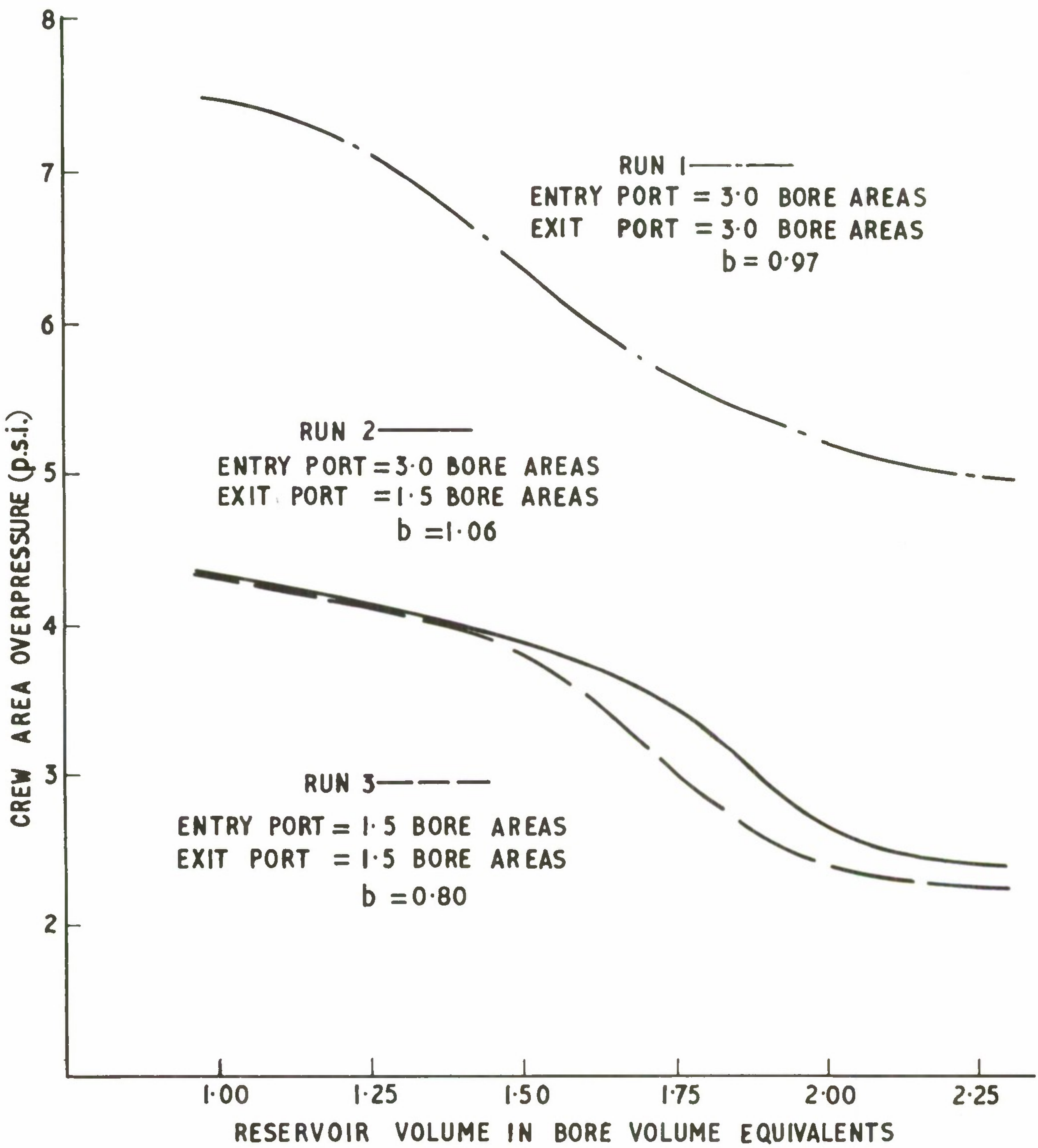

FIG. 4 OVERPRESSURE VS RESERVOIR VOLUME

FIG. 5

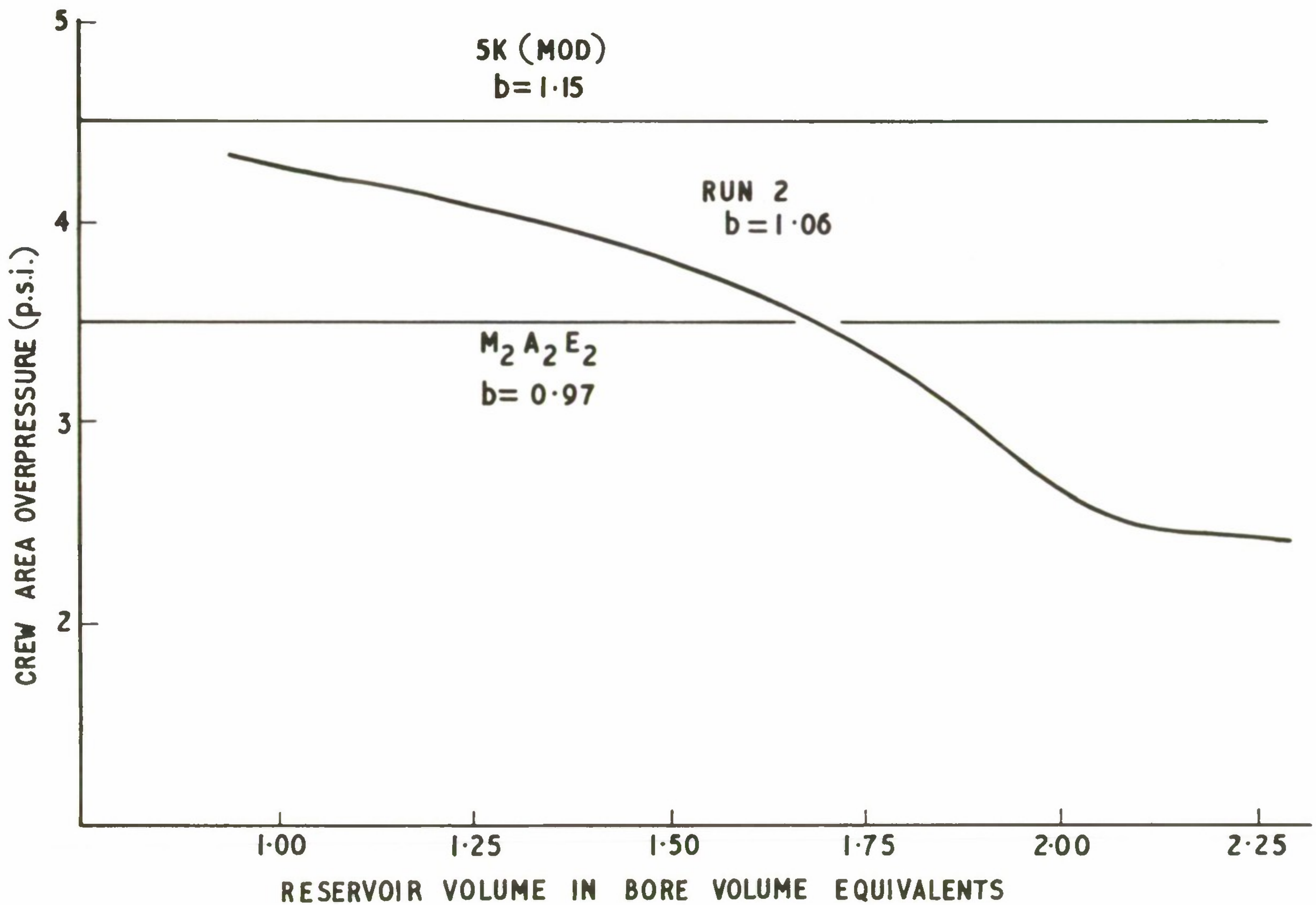

FIG. 5 OVERPRESSURE VS RESERVOIR VOLUME

FIG. 6

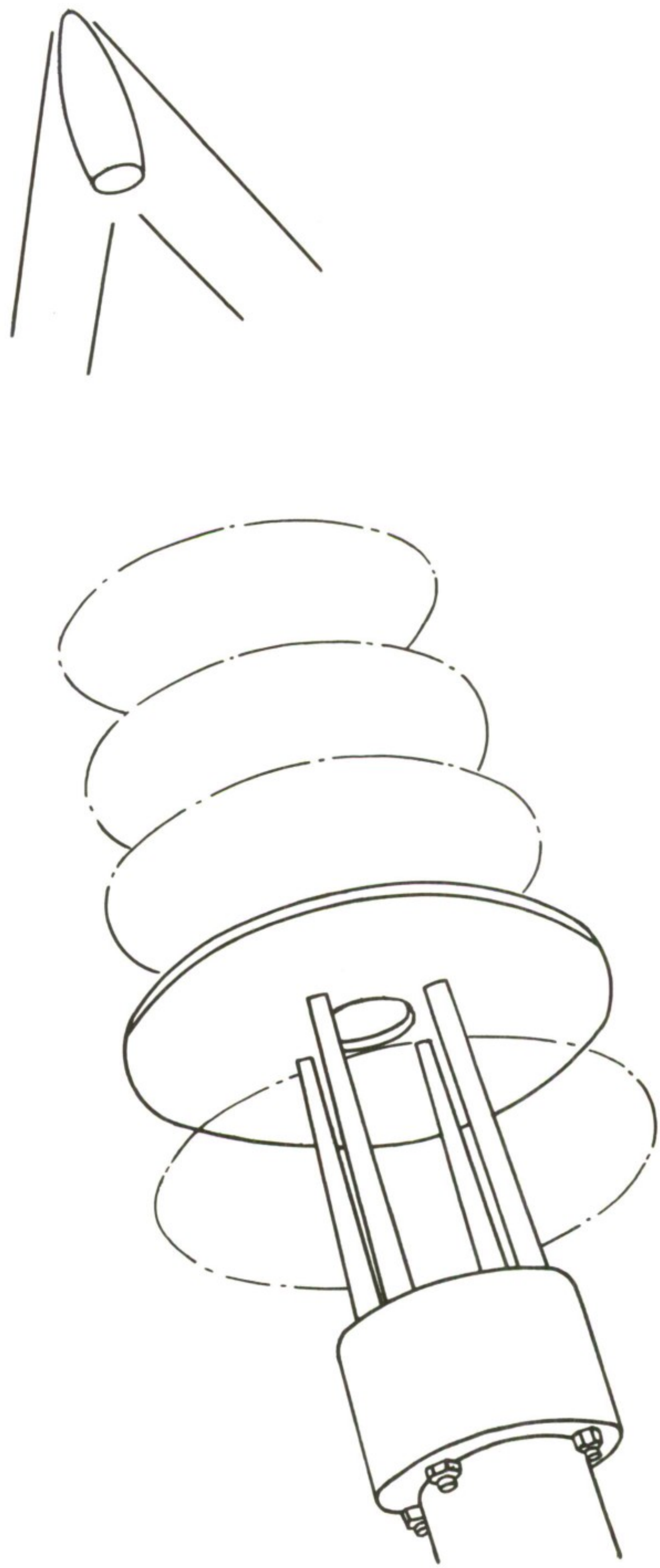

FIG. 6 TEST FIXTURE

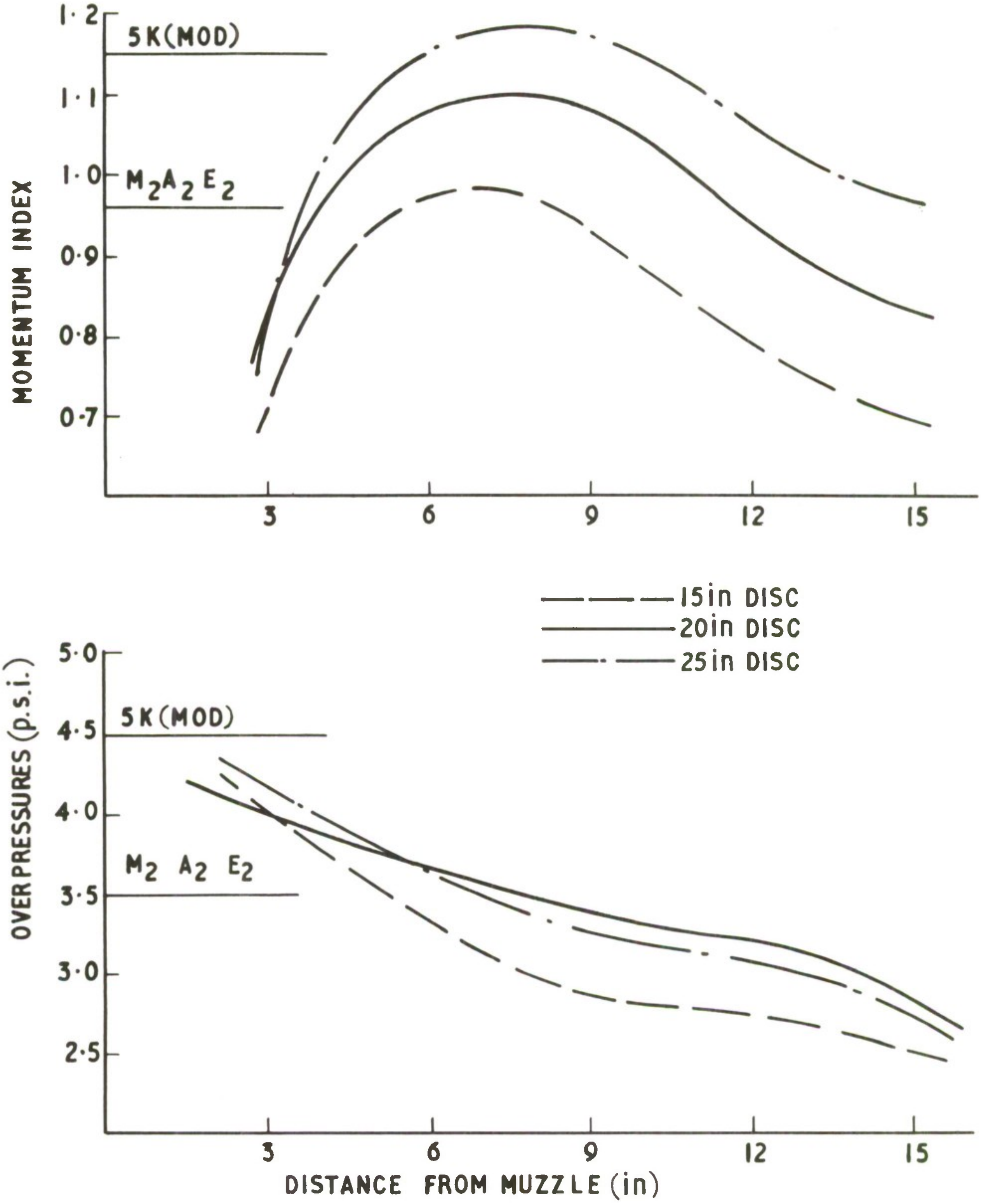

FIG. 7 SINGLE BAFFLE RESULTS

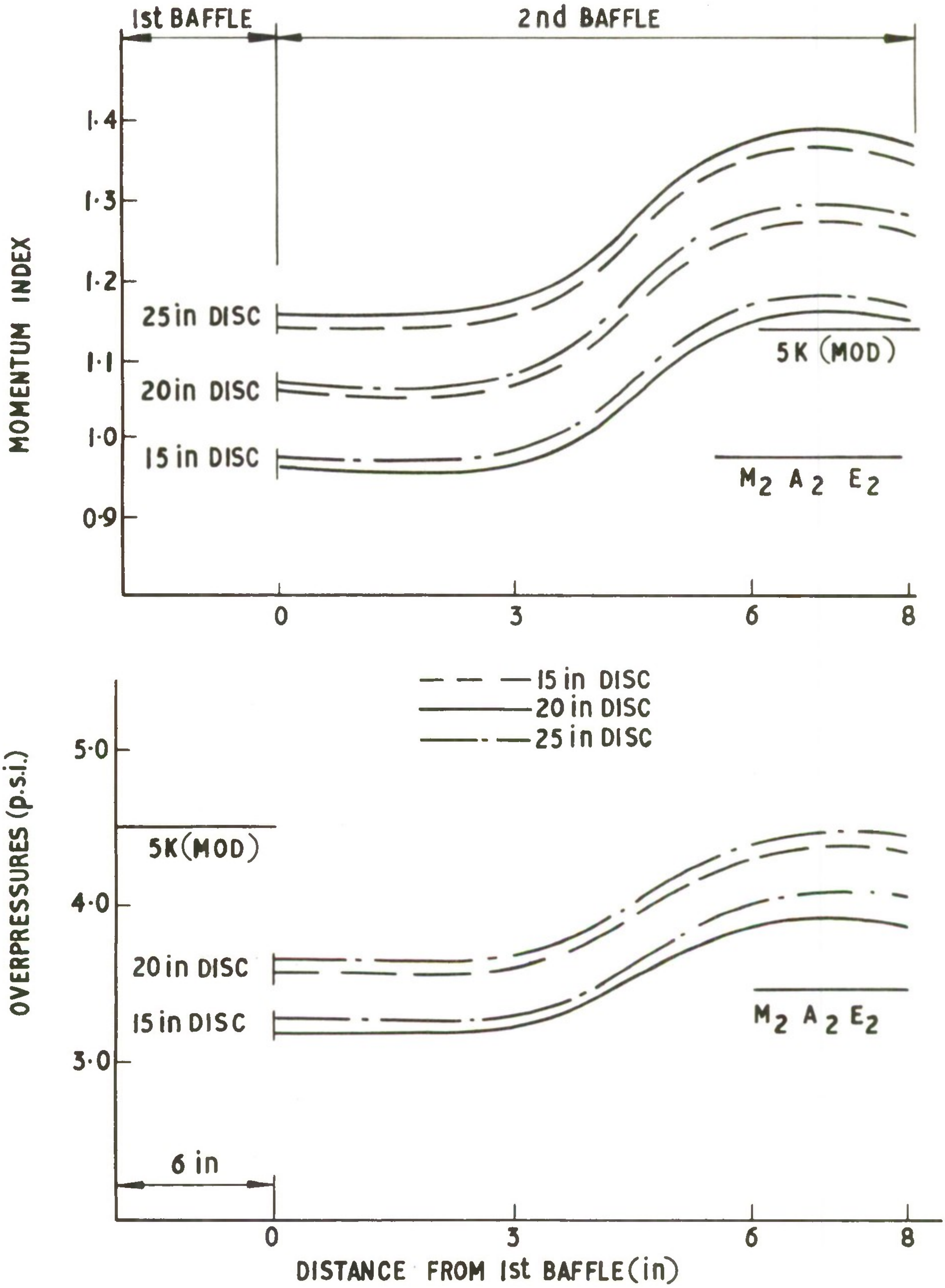

FIG.8 DOUBLE BAFFLE RESULTS

FIG. 9

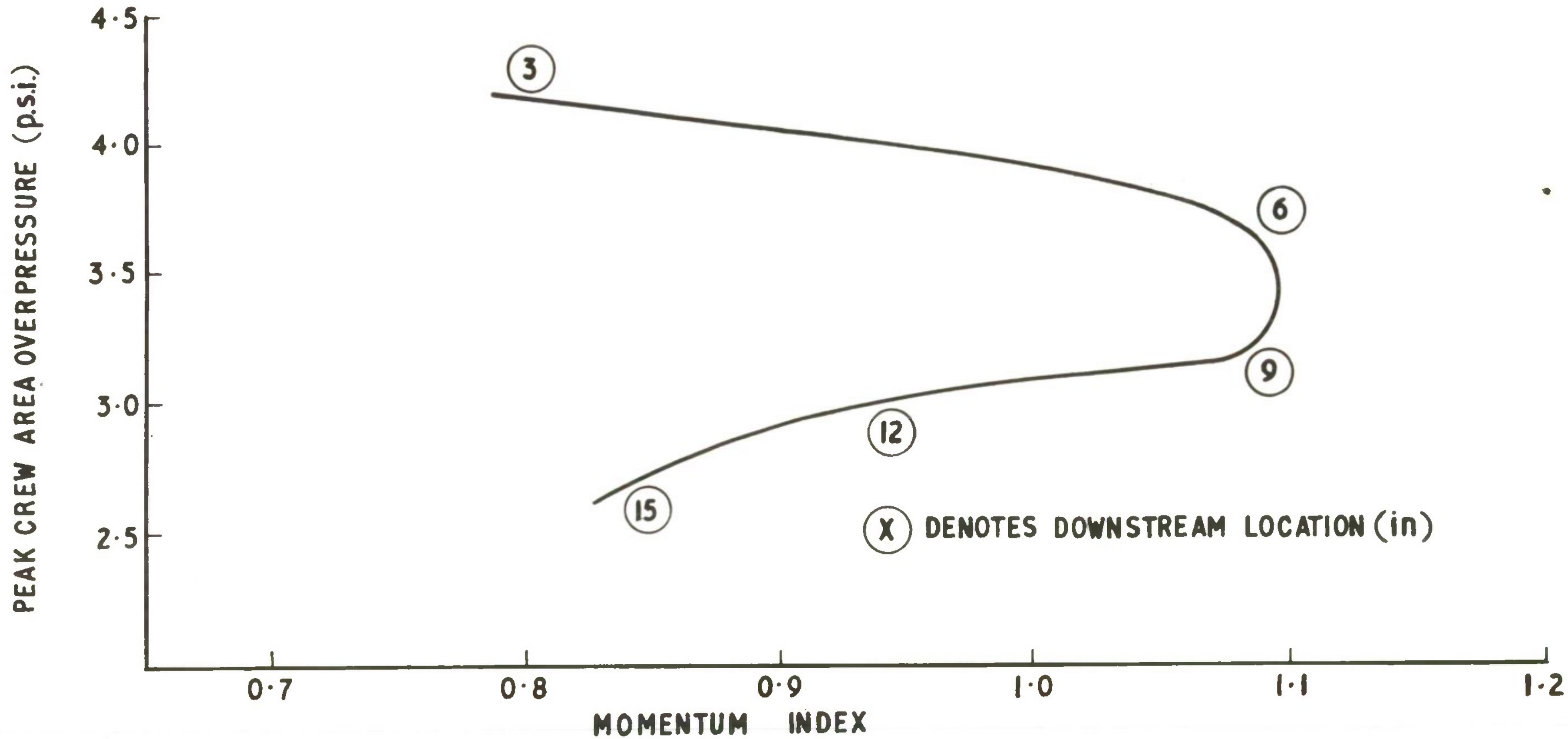

FIG. 9 OVERPRESSURE VS EFFICIENCY—(20 in DISC)

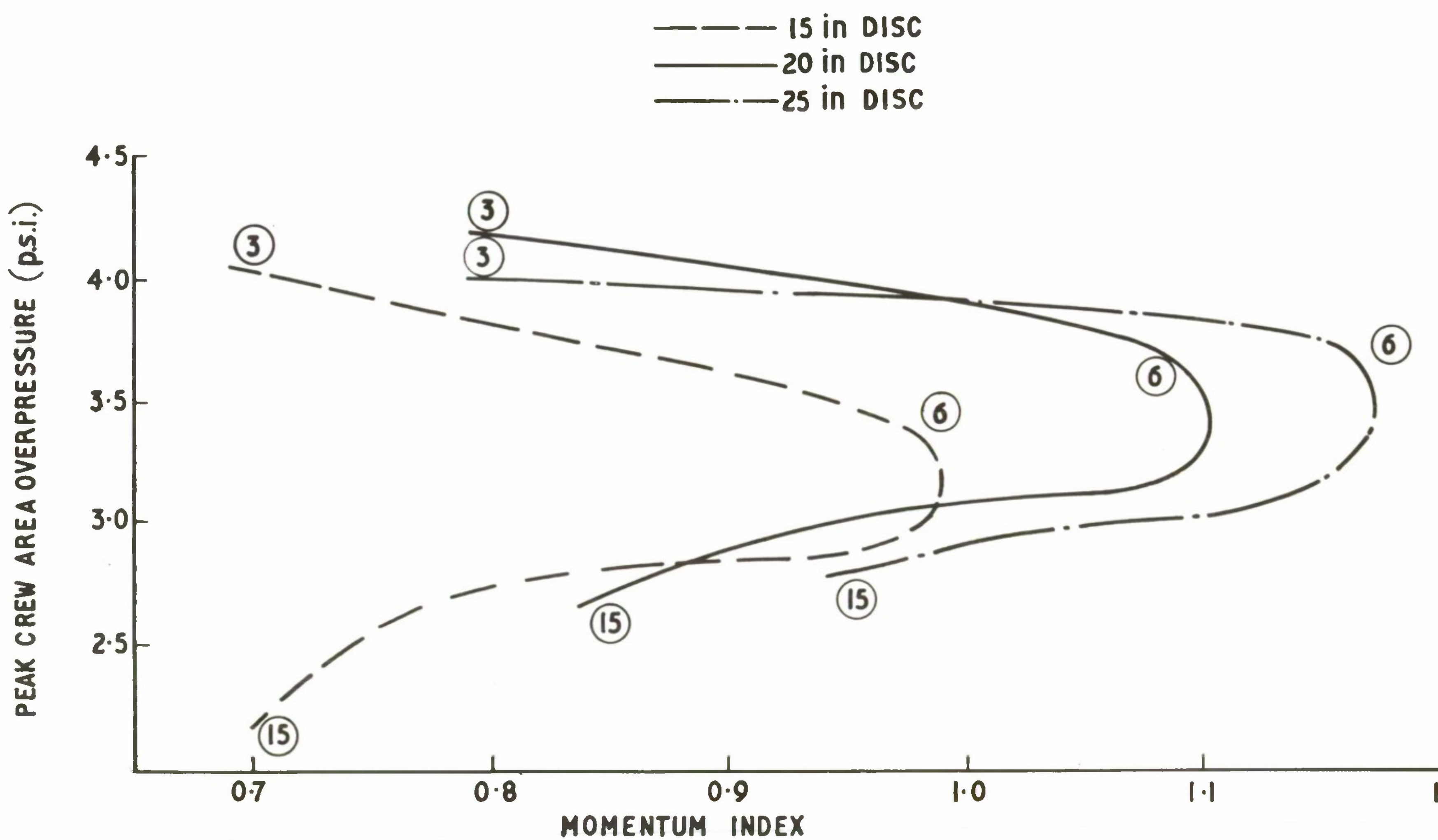

FIG. 10 OVERPRESSURE VS EFFICIENCY — VARIOUS DISCS

FIG. 10

SESSION II
Item 6

Session II
Item 6 M109 Test firings with US and FRG muzzle brakes and XM 119 charges

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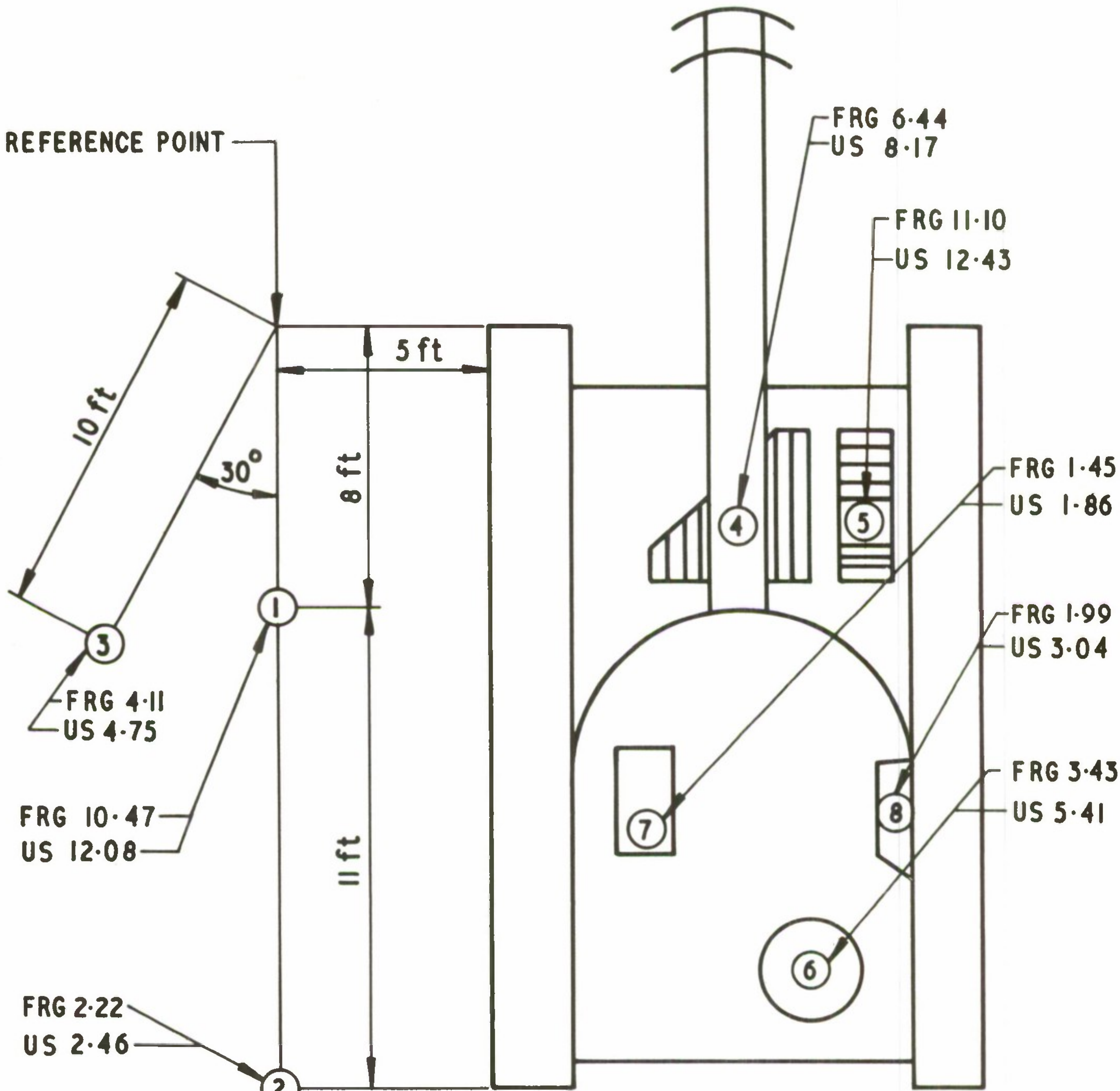

FIG.1(a) GAUGE POSITION AND PEAK BLAST PRESSURES FOR US AND FRG MUZZLE BRAKES ON M 109 — 0° ELEVATION

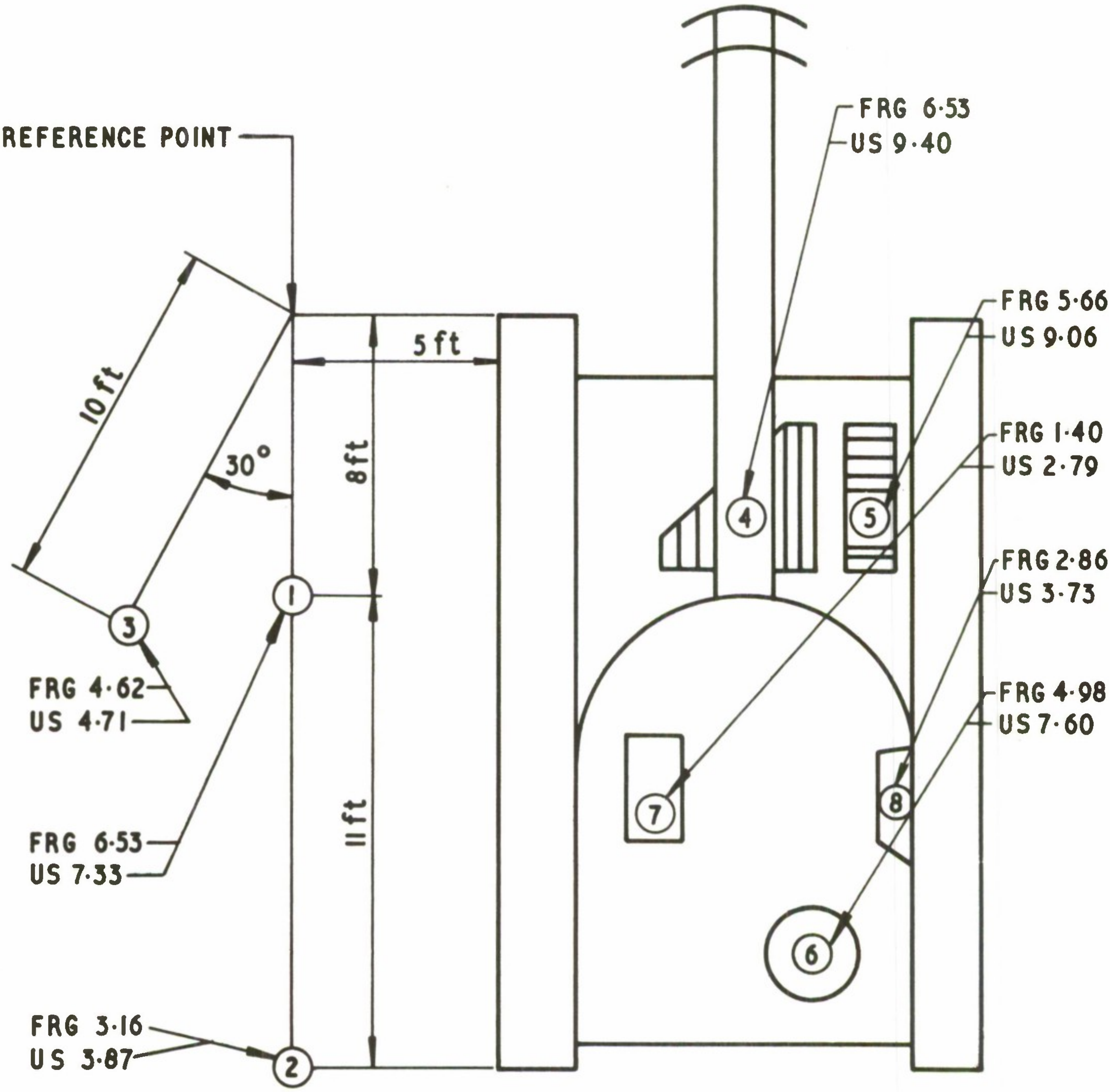

FIG.1(b) GAUGE POSITION AND PEAK BLAST PRESSURES FOR US AND FRG MUZZLE BRAKES ON M109–70° ELEVATION

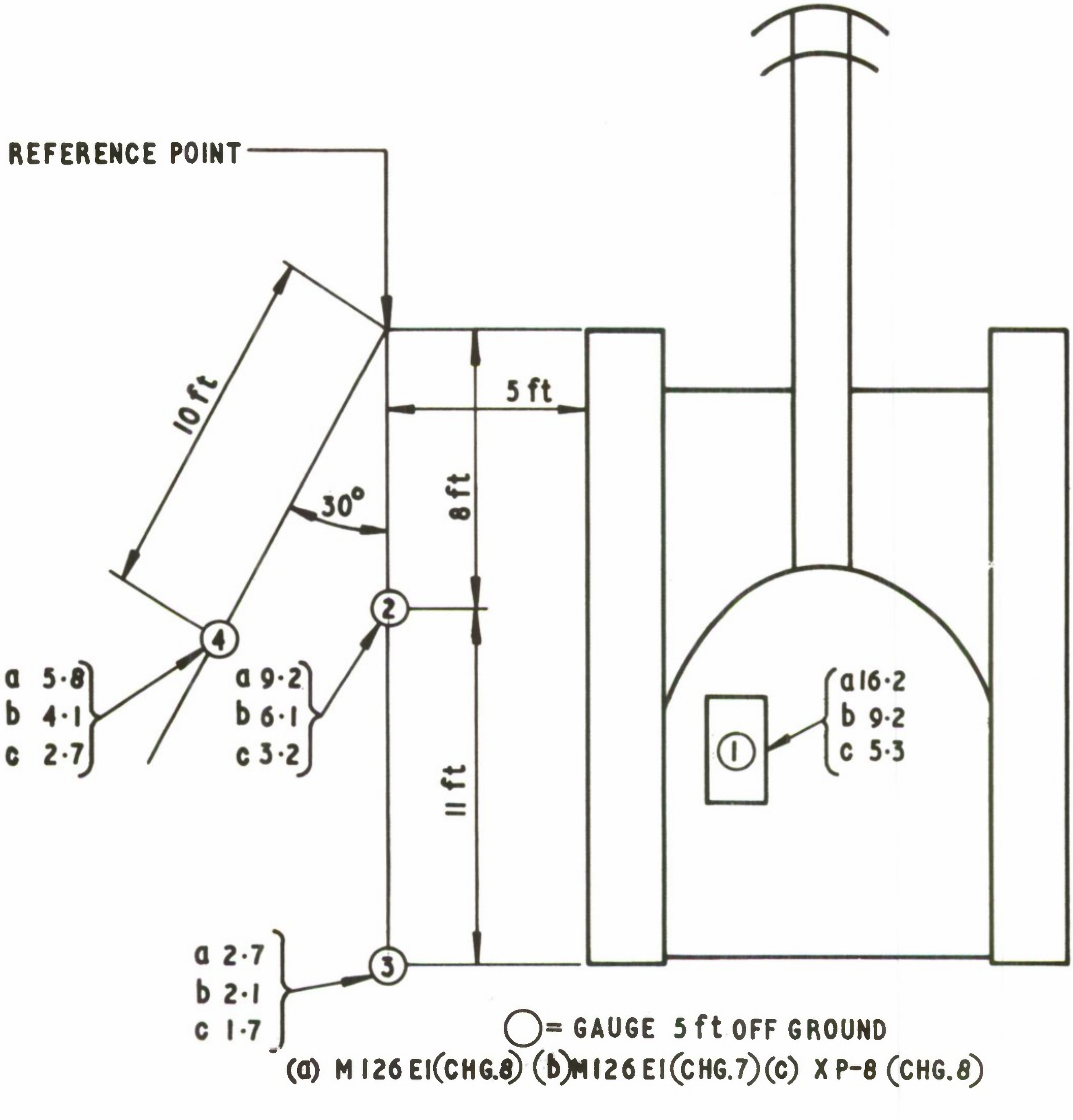

FIG.2 GAUGE POSITION AND PEAK BLAST PRESSURES FOR STANDARD AND LONG BARRELS ON M109 WITH STANDARD MUZZLE BRAKES

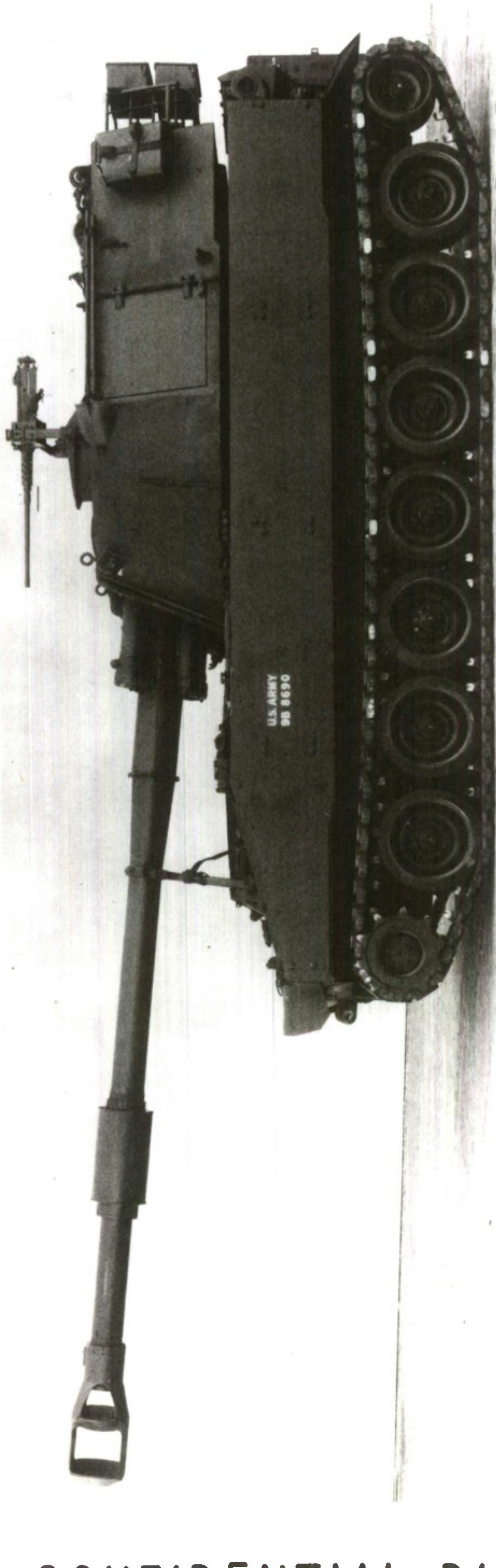

FIG.3 M 109 WITH LONG BARREL

TABLE 1

M109 - XM119E4 Charge Compatibility Test

(US Muzzle Brake)

Tecom Project No. 2-3-0027-56

Failure Summary - Veh. No. 12DB57

No.	Component Nomenclature	Miles	Rounds	Federal Defect Classification
1.	Retainer ring, bore evacuator	-	53	Deficiency
2.	Grille support assy bracket	-	152	Shortcoming
3.	Support assy, top base	49	241	Shortcoming
4.	Grille support plate	371	-	Shortcoming
5.	Handle, transmission access door	1728	-	Shortcoming
6.	Grille handle	1728	-	Shortcoming
7.	Hinge, driver's periscope door	1808	-	Shortcoming
8.	Bracket, pan. tel. stowage box	1912	1260	Shortcoming
9.	Fuse pack, right front mounting holes	1912	1260	Shortcoming
10.	Latch, air cleaner access	1912	1260	Shortcoming
11.	Fuze rack, left rear	1960	1420	Shortcoming
12.	Muzzle brake	-	1476	Deficiency
13.	Bore evacuator, rear ring	-	1476	Shortcoming
14.	Hatch cover, latch pin	1976	1480	Shortcoming
15.	Flare rack bottom brackets	1976	1540	Shortcoming
16.	Stowage baskets	1976	1570	Shortcoming
17.	Bore evacuator	1976	1705	Shortcoming
18.	Commander Cupola latch retaining screw	1976	1735	Shortcoming
19.	Drivers periscope door	2185	2002	Shortcoming

TABLE 2

M109 - XM119E4 Charge Compatibility Test

(FRG Muzzle Brake)

Tecom Project No.2-3-0027-77

Failure Summary - Veh. No.12A36766

No.	Component Nomenclature	Miles	Rounds	Federal Defect Classification
1	Grille Plate	96	40	Shortcoming
2	Radiator, Fins (bent over)*	121	107	Shortcoming
3	Air cleaner control handle	240	432	Shortcoming
4	Seal, Turret Race	251	507	Deficiency
5	Bracket, Flotation Hose Cover	265	527	Shortcoming
6	Cover, spare periscope box	265	527	Shortcoming
7	Valve cover and gasket, engine	293	657	Deficiency
8	Panoramic Telescope	293	657	Deficiency
9	Web strap - Travel lock tie down	307	707	Shortcoming
10	Bore evacuator assembly	346	957	Deficiency
11	Heat shield	359	1057	Shortcoming
12	Hanger, Exhaust Pipe	359	1057	Shortcoming
13	Gasket, Rocker Arm Cover	359	1057	Deficiency
14	Holder, Flashlight	359	1057	Shortcoming
15	Counter, Panoramic Telescope	373	1059	Deficiency
16	Alternator (Generator)	-	1362	Deficiency
17	Pin, Guide, Recuperator	582	1722	Deficiency
	*Occurred also at	359	1057	
		582	1722	

Session II
Item 7 The Interaction of the man-weapon system and studies involving muzzle gas dynamics

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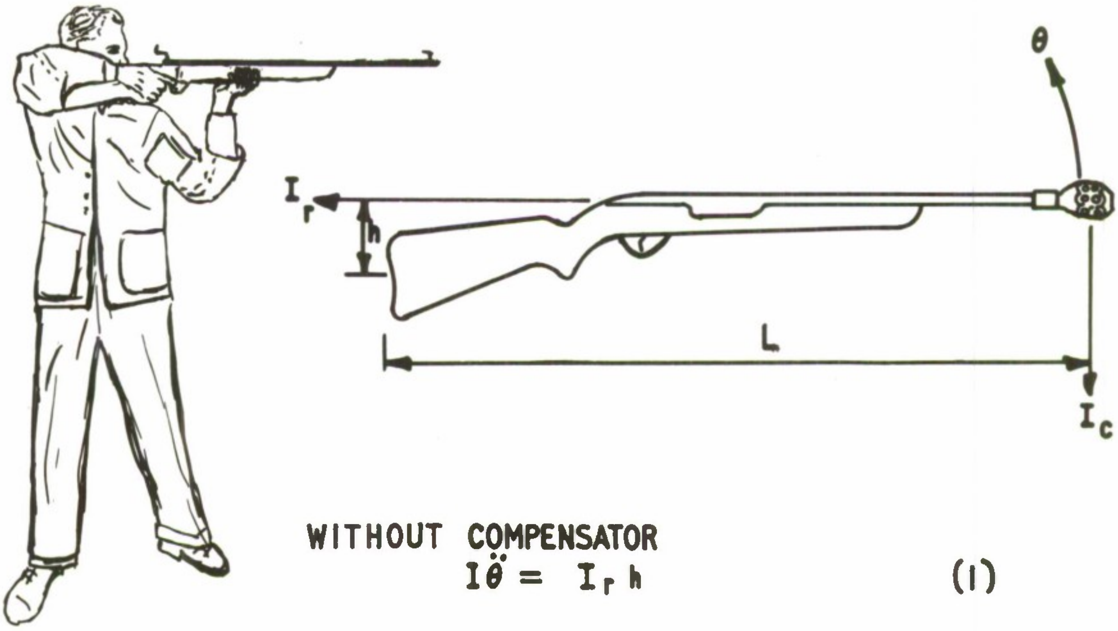
FIG. 1



WITHOUT COMPENSATOR

$$I\ddot{\theta} = I_r h \qquad (1)$$

WITH COMPENSATOR

$$I\ddot{\theta} = I_r h - I_c L \qquad (2)$$

FIG.1 MATHEMATICAL MODEL OF THE MAN-WEAPON SYSTEM

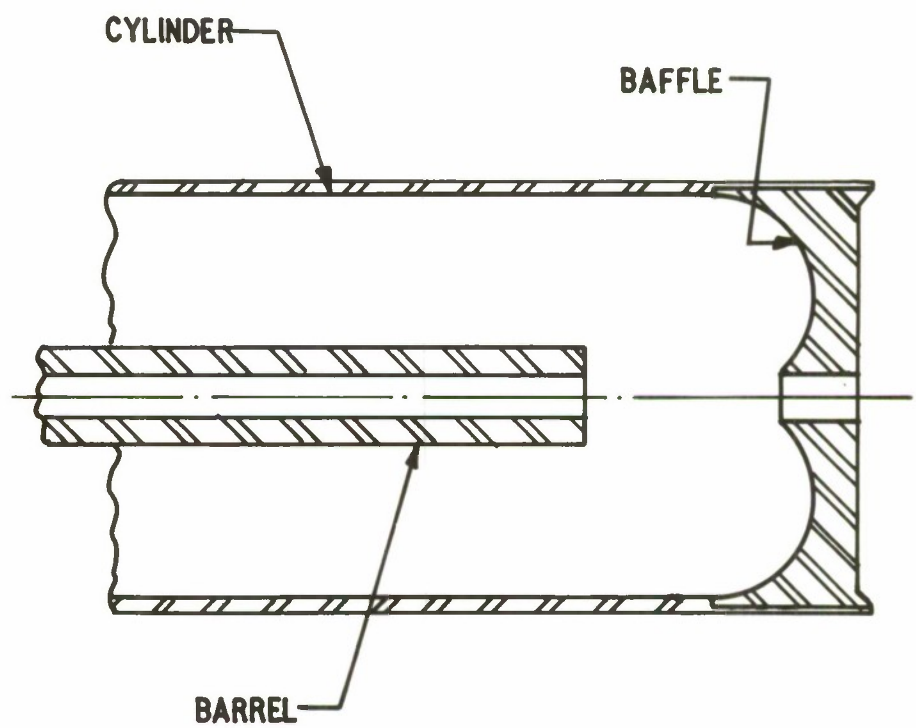


FIG. 2 MUZZLE BRAKE FOR CAL. 0·22 RIFLE

FIG. 3

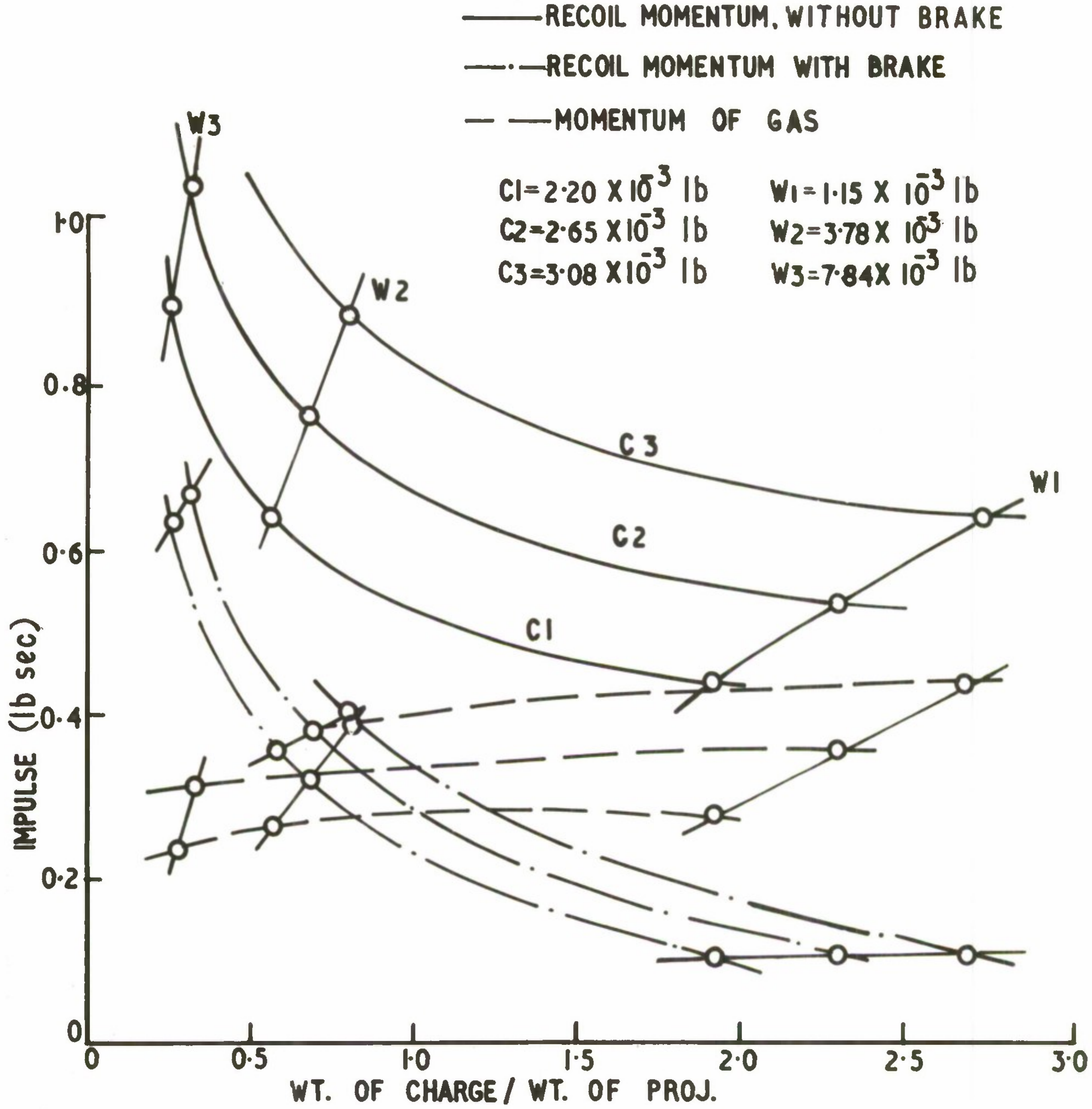
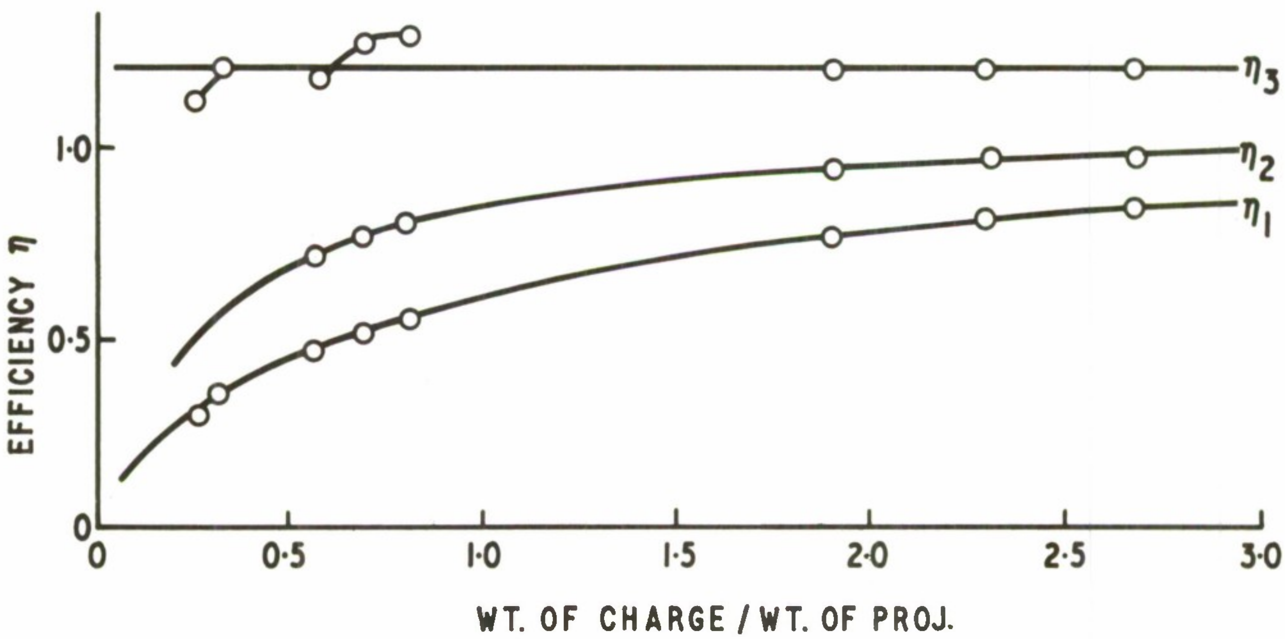


FIG. 3 MOMENTUM OF CAL. 0·22 RIFLE

FIG.4



η_1 BASED ON RECOIL ENERGY

η_2 BASED ON RECOIL MOMENTUM

η_3 BASED ON MOMENTUM OF GAS

FIG. 4 EFFICIENCY OF CAL. 0·22 BRAKE

Session III
Item 1.2 Communication problems with intermittent impulse noises

Table 1 Peak levels of impulse noises

TABLE 1.

HAZARD		NOISE	
Lung Damage	15 p.s.i.		
Eardrum Rupture	5 p.s.i.	Artillery, Carl Gustav, Mortars (guncrew)	1 – 8 p.s.i.
Hearing Damage (to 25%, 1-2 round exposures)	170 dB* = 1 p.s.i. (grazing incidence)	7.62 mm Rifle (man 3' at 060°)	170 dB* = 1 p.s.i. (normal incidence)
Hearing Damage (to 25%, 100 round exposures)	160 dB = 0.3 p.s.i. (grazing incidence)	7.62 mm Rifle (Firer)	160 dB = 0.3 p.s.i. (grazing incidence)
Hearing Damage (to 1%, 100 round exposures)	140 dB (reverberant field)	0.22 in. Rifle (Firer)	140 dB = 0.03 p.s.i. (grazing or reverberant)
		Sonic Boom	134 dB = 2 p.s.f.

*decibels (dB) peak level, reference 0.0002 dyne/sq.cm.

SESSION III
Item 1·3

Session III
Item 1.3 Auditory damage risk from impulse noise

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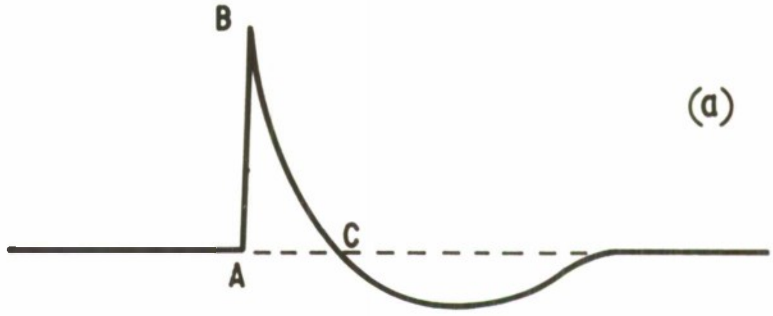

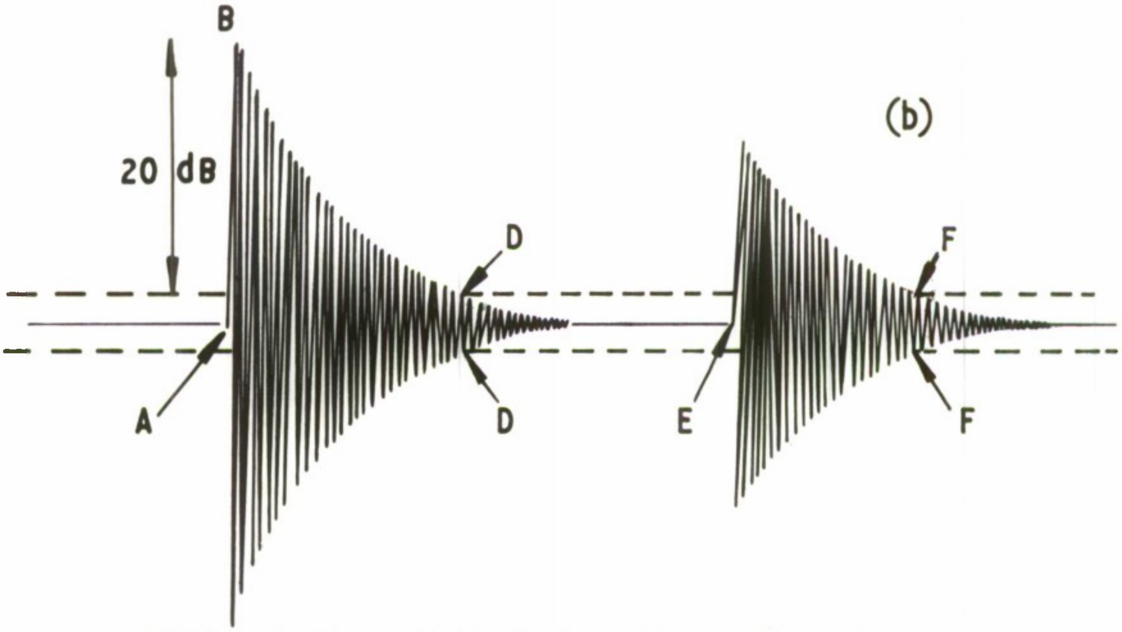

PEAK LEVEL = PRESSURE DIFFERENCE A B

RISE TIME = TIME DIFFERENCE A B

(a) A DURATION = TIME DIFFERENCE A C

(b) B DURATION = TIME DIFFERENCE A D (+ E F FOR EXAMPLE IN THE CASE OF A RELATIVELY LONG TIME REFLECTION)

FIG. 1 IDEALIZED EVALUATION OF OSCILLOGRAPHIC WAVEFORMS OF IMPULSE NOISES

FIG.2

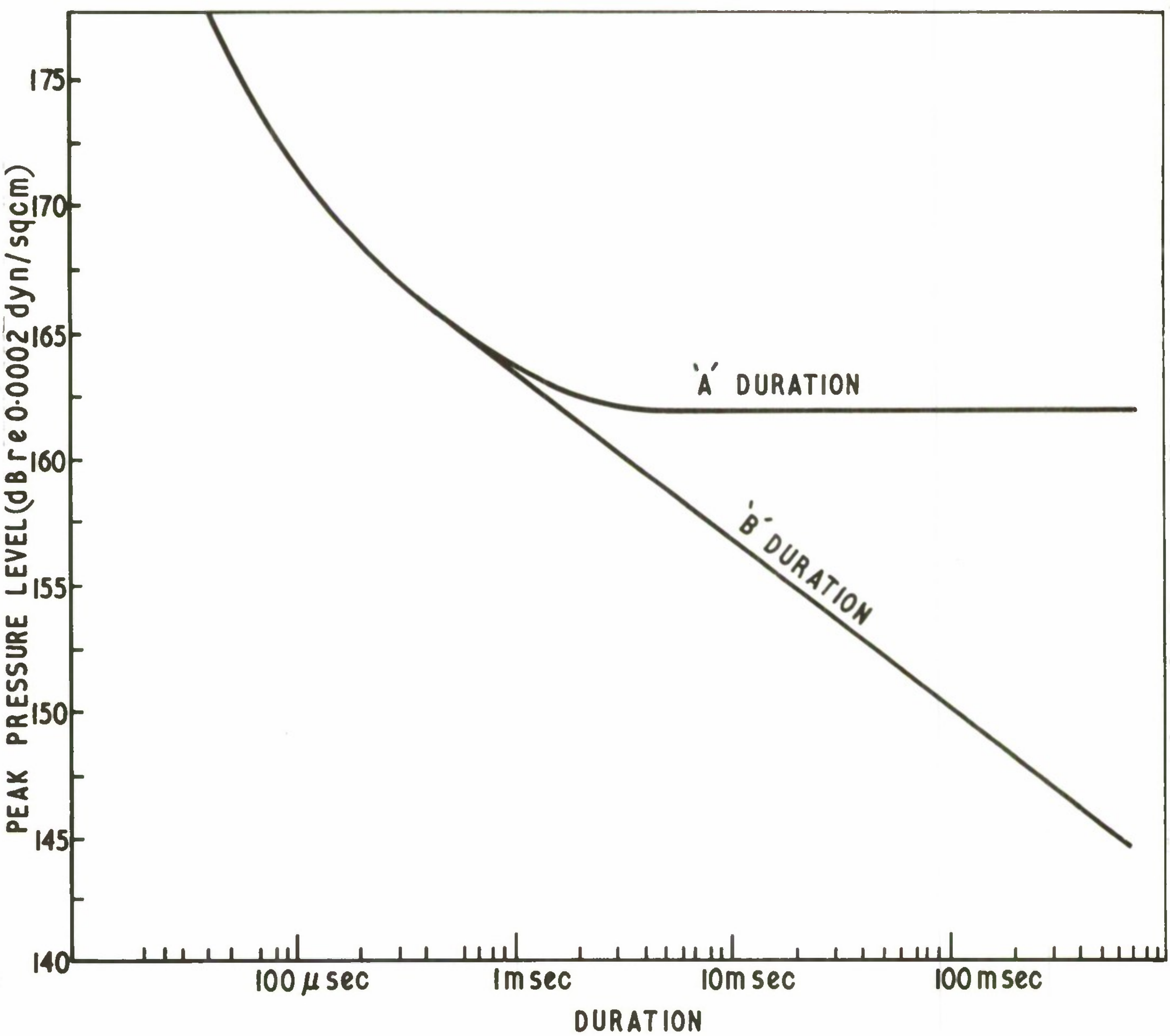

FIG. 2 DAMAGE RISK CRITERION FOR IMPULSE NOISE

Session III
Item 3 The effects of gun blast on hearing

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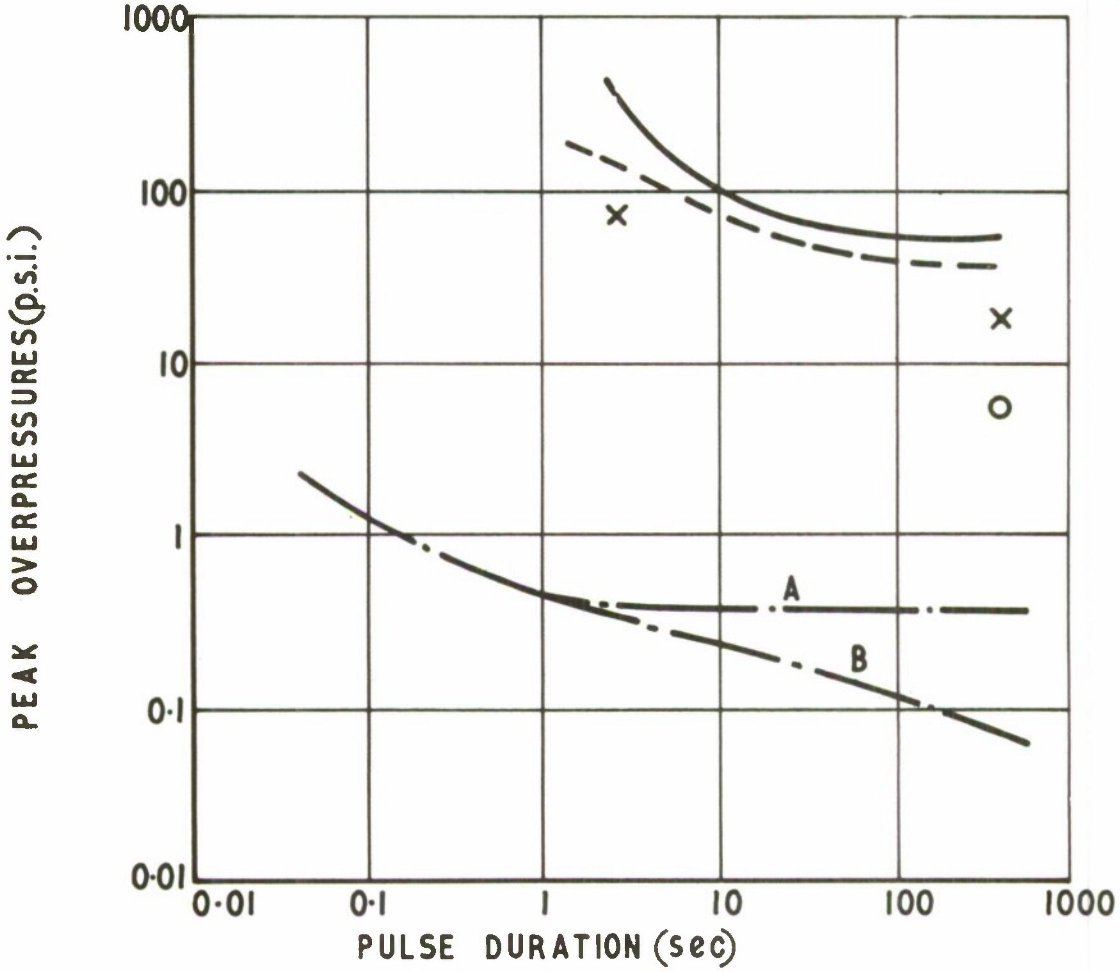
FIG.1



NOTES:

———	50% LETHALITY
– – – –	THRESHOLD OF LETHALITY (BOTH FROM ANIMAL EXPERIMENTS EXTRAPOLATED TO MAN)
×	ESTIMATES OF THRESHOLD OF LUNG DAMAGE
O	ESTIMATE OF THRESHOLD OF EAR DRUM RUPTURE IN MAN (ALL ABOVE ARE FOR SINGLE EXPOSURES)
—·—·—	LIMIT FOR DAILY EXPOSURE TO 100 ROUNDS ABOVE WHICH INNER EAR DEAFNESS MAY OCCUR; A, WHEN TIME FOR INITIAL TRANSIENT TO DECAY TO 1/10 AMPLITUDE IS KNOWN B, WHEN TIME FOR ENVELOPE DRAWN AROUND SUBSEQUENT OSCILLATION HAS DELAYED TO 1/10 AND INITIAL AMPLITUDE IS KNOWN

FIG.1 PEAK OVERPRESSURES AND PULSE DURATION FOR BLAST INJURY

For Indexing

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Ministry of Defence
Royal Armament Research and Development Establishment
R.A.R.D.E. Memorandum 34/70

061.3:
623.532:
623.4.067

Gun Blast and Muzzle Brake Symposium
R.A.R.D.E. Fort Halstead 5th - 7th March 1968 (U)

G. R. Nice

November 1970

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